1993

Hybrid power system for remote communications stations

Pietras, Christopher R.

Monterey, California. Naval Postgraduate School

http://hdl.handle.net/10945/39988

2

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

HYBRID POWER SYSTEM
FOR
REMOTE COMMUNICATIONS STATIONS

by

Christopher R. Pietras

September, 1993

Thesis Advisor: Sherif Michael

Approved for public release; distribution is unlimited.

Unclassified
Security Classification of this page

REPORT DOCUMENTATION PAGE

1a Report Security Classification: Unclassified	1b Restrictive Markings
2a Security Classification Authority	3 Distribution/Availability of Report Approved for public release; distribution is unlimited.
2b Declassification/Downgrading Schedule	
4 Performing Organization Report Number(s)	5 Monitoring Organization Report Number(s)
6a Name of Performing Organization Naval Postgraduate School / 6b Office Symbol *(if applicable)* EC	7a Name of Monitoring Organization Naval Postgraduate School
6c Address *(city, state, and ZIP code)* Monterey, CA 93943-5000	7b Address *(city, state, and ZIP code)* Monterey, CA 93943-5000
8a Name of Funding/Sponsoring Organization / 8b Office Symbol *(if applicable)*	9 Procurement Instrument Identification Number
8c Address *(city, state, and ZIP code)*	10 Source of Funding Numbers Program Element No / Project No / Task No / Work Unit Accession No

11 Title *(include security classification)* HYBRID POWER SYSTEM FOR REMOTE COMMUNICATIONS STATIONS

12 Personal Author(s) Christopher R. Pietras

13a Type of Report	13b Time Covered	14 Date of Report *(year, month, day)*	15 Page Count
Master's Thesis	From To	1993 September	187

16 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17 Cosati Codes			18 Subject Terms *(continue on reverse if necessary and identify by block number)*
Field	Group	Subgroup	Hybrid Power System, Solar Power System, Wind Power System, Photovoltaic

19 Abstract *(continue on reverse if necessary and identify by block number)*

The United States Coast Guard is upgrading communications equipment at remote sites in Alaska in support of the Coastal Voice Distress Network. The VHF-FM Search and Rescue sites are powered by a primary power system consisting of a thermoelectric generator. Thermoelectric generators are very inefficient devices which consume vast quantities of propane to create electricity. The upgrade necessitates added power requirements on the power supply system at the remote sites. These requirements compel the redesign and/or upgrade of the power system. If thermoelectric generators continue to be utilized as the primary power system, additional helicopter visits to the sites to deliver propane will be required. These helicopter flights are costly and sometimes hazardous due to severe weather.

This thesis investigates a variety of power system options capable of providing electrical power to the communications sites. Specifically, this thesis addresses three objectives. The first is a discussion of current alternative energy source technology available to supply the required power. The second is an analysis of the specific power system requirements and constraints. The third objective and major thrust of the research, is the design of a reliable hybrid power system for this application, capable of utilizing the inexhaustible natural energy available at the remote sites. The engineering parameters for a hybrid power system were studied and calculations made based on commercially available components. The difficulties in the design due to extreme weather conditions and unavailability of natural power resource information at specific sites are addressed. This thesis presents the groundwork associated with hybrid power system designs for use at remote communications sites.

20 Distribution/Availability of Abstract X unclassified/unlimited _ same as report _ DTIC users	21 Abstract Security Classification Unclassified	
22a Name of Responsible Individual Sherif Michael	22b Telephone *(include Area Code)* (408) 656-2252	22c Office Symbol EC/Mi

DD FORM 1473,84 MAR 83 APR edition may be used until exhausted security classification of this page

All other editions are obsolete Unclassified

Approved for public release; distribution is unlimited.

Hybrid Power System
for
Remote Communications Stations

by

Christopher R. Pietras
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1983

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
[redacted]

Author: [redacted]
Christopher R. Pietras

Approved by: [redacted]
Sherif Michael, Thesis Advisor

[redacted]
Robert W. Ashton, Second Reader

[redacted]
Michael A. Morgan, Chairman
Department of Electrical and Computer Engineering

ABSTRACT

The United States Coast Guard is upgrading communications equipment at remote sites in Alaska in support of the Coastal Voice Distress Network. The VHF-FM Search and Rescue sites are powered by a primary power system consisting of a thermoelectric generator. Thermoelectric generators are very inefficient devices which consume vast quantities of propane to create electricity. The upgrade necessitates added power requirements on the power supply system at the remote sites. These requirements compel the redesign and/or upgrade of the power system. If thermoelectric generators continue to be utilized as the primary power system, additional helicopter visits to the sites to deliver propane will be required. These helicopter flights are costly and sometimes hazardous due to severe weather.

This thesis investigates a variety of power system options capable of providing electrical power to the communications sites. Specifically, this thesis addresses three objectives. The first is a discussion of current alternative energy source technology available to supply the required power. The second is an analysis of the specific power system requirements and constraints. The third objective and major thrust of the research, is the design of a reliable hybrid power system for this application, capable of utilizing the inexhaustible natural energy available at the remote sites. The engineering parameters for a hybrid power system were studied and calculations made based on commercially available components. The difficulties in the design due to extreme weather conditions and unavailability of natural power resource information at specific sites are addressed. This thesis presents the groundwork associated with hybrid power system designs for use at remote communications sites.

Accesion For	
NTIS CRA&I	X
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I wish to recognize my thesis advisor, Dr. Sherif Michael, for his guidance, attentiveness and support. Thank you for contributing to my understanding and learning.

Thanks to Michael Bergey, President, Bergey Windpower Company, for providing me with wind turbine information.

Many thanks to Professor Bob Ashton for his comments and questions.

Love and thanks to my son and daughter, Michael and Katie, for their understanding and patience during the many hours I have spent away from them while working on this project.

Additionally, I would like to thank all who have listened (while I complained) and offered advice (which I sometimes recklessly disregarded).

It is with deepest gratitude that I acknowledge my wife, Jennifer, for her continuous support, confidence, love and understanding over the past two and one half years. And last but certainly not least, I wish to thank her for her typing and proofreading skills which have made possible this seemingly impossible task. I dedicate this thesis to her.

I. INTRODUCTION

A. OBJECTIVE

The objective of this thesis was to analyze alternative strategies for supplying the power required to support the communications loads of remote sites. Additionally, this thesis examined a specific application in which a typical hybrid power system is to be operated in conjunction with the currently installed power system to support higher power requirements brought on by the addition of new communication equipment at a remote location.

B. OVERVIEW

The United States Coast Guard, Maintenance and Logistics Command Pacific, Alameda, California, is presently replacing existing communications equipment at remote communications sites. This equipment, the foundation of Alaska's Coastal Voice Distress Network (CVDN), requires more power to operate.

The updated communications equipment (VHF-FM radios and antennas) at the remote sites in Alaska will provide enhanced communications capability for the Coast Guard. The VHF-FM Search and Rescue sites are powered by a primary power system consisting of a thermoelectric generator. Thermoelectric generators are very inefficient devices that consume vast quantities of propane to generate electricity. The upgrade of

the communications system necessitates additional propane or an upgrade and/or redesign of the power system at the site. If thermoelectric generators continue as the primary power system, additional helicopter flights to the sites to deliver propane will be required. These helicopter flights are costly and sometimes hazardous due to severe weather.

This research was undertaken to investigate a variety of power system options capable of furnishing electrical power to the remote sites of the CVDN, operated by the Coast Guard. To this end, this presentation will address three objectives. The first is a discussion of current alternative energy source technology available to supply the required electrical power. The second is an analysis of the specific power system requirements and constraints. The third objective and major thrust of the research, is to design a reliable hybrid power system for this application, capable of utilizing the inexhaustible natural energy available at the communications sites.

The advantages, disadvantages and techniques of the alternatives are discussed and an in-depth analysis is made of a typical hybrid alternative. The hybrid power system design incorporates solar panels and wind turbines, with a thermoelectric generator backup. Additionally, the difficulties in the design due to the extreme weather conditions and the unavailability of natural power resource information at specific sites are addressed.

C. ORGANIZATION

This thesis is divided into nine chapters. This chapter provides an overview of the entire thesis and the expected benefits of the research.

Chapter II delineates the requirements and constraints of the power system design with respect to the Coast Guard application. It also provides background on the Coastal Voice Distress Network.

Chapter III describes thermoelectric generators. Additionally, it reviews the advantages and disadvantages of using a thermoelectric generator as the only power source supporting the communications sites.

The potential alternative power supplies for remote communications sites are described in Chapter IV. The hybrid power system design originates from this chapter.

Chapter V gives a brief history of solar cell development and also describes operating principles and electrical considerations. This chapter finishes with a discussion of a power system design for the Coast Guard application using only solar panels.

Wind generators and a wind power use are described in Chapter VI. A wind only power system with respect to the Coast Guard application in Alaska is also presented.

Chapter VII discusses battery storage possibilities. A battery storage system is presented for the specific Coast Guard application.

Chapter VIII presents a typical hybrid power system design. This design is optimized specifically for the Coast Guard application in Alaska.

Chapter IX summarizes the salient features of the thesis and presents conclusions and suggestions for further research.

D. SCOPE

It is not the intention of this thesis to engineer a completely detailed system for the Coast Guard facility, but merely to present a typical hybrid model and evaluate new technology that could be considered for future applications.

The scope of this investigation was to:

- Study the limitations imposed by the application sites in Alaska.
- Evaluate alternative power supply options.
- Present and discuss a typical hybrid power system design with respect to the Coast Guard communications sites in Alaska.
- Provide direction and recommendations for future research in the area of hybrid power system design for remote communications stations.

This investigation did not cover:

- Specific equipment recommendations for the typical hybrid system.
- Final optimization of the hybrid model, due to the need of specific and current site data.
- Power system cost analysis.

E. EXPECTED BENEFITS

This study is intended to be used for the specific Coast Guard application in Alaska. However, the results of this thesis can be used as a baseline for other remote communication power system designs.

The contribution of this thesis is to provide a better understanding of the criteria used to select a specific alternative from a range of options. This study provided the groundwork for the utilization of solar panels and wind turbines in combination with thermoelectric generators in a hybrid model designed for use in remote communications sites.

II. DESIGN SPECIFICATIONS

A. BACKGROUND

Currently the power requirements for most United States Coast Guard remote communications sites in Alaska are supplied by thermoelectric generators. Thermoelectric generators are very inefficient devices that burn propane to generate electricity. They are discussed in detail in Chapter III.

The existing communications equipment at the remote sites will be replaced by enhanced equipment which uses even more power. An alternate power system must be developed or even larger amounts of propane must be transported by helicopter to the sites to meet the additional power requirements of the communications load.

1. Coastal Voice Distress Network

The Coastal Voice Distress Network (CVDN), operated and maintained by the United States Coast Guard, is a series of remote communications and microwave repeater sites along the coastline and islands of Alaska These communications sites, as documented in Appendix A, provide the ability for the U.S. Coast Guard to monitor communications and transmit to vessels, both foreign and domestic, that are operating along the southern coastline of Alaska. The capability to reliably and efficiently monitor and transmit to vessels in these

waters enables the Coast Guard to dispatch search and rescue personnel, ships and aircraft to ships in distress. Reliability of the communications suite is of major concern and consequently the reliability of the power system selected for the remote site used to support the CVDN is of prime importance. As the systems are remotely located, they cannot be routinely maintained. Accordingly, the power system that is selected must have a high degree of reliability and must be able to operate in a wide range of environmental conditions.

B. REQUIREMENTS

In order to determine the feasibility of replacing the old power system with a new power system design, it is necessary to examine the system requirements and constraints that have been set by the United States Coast Guard, Maintenance and Logistics Command Pacific, as well as those that exist due to environment and locale.

1. Power Requirements

Two separate power system designs are needed. One is for an entire remote communications site, while the other is for a microwave relay site. The sponsor has specified the following power requirements for the design.

a. Main Communications Sites

For design and calculation purposes, a power consumption of 300 watts, 90 percent of the time, and 500 watts, 10 percent of the time, at 24V DC, was assumed to be

the maximum power requirement for the main communications system.

The 300 watt requirement at a 90 percent duty cycle, corresponds to 270 W, continuous (assuming large storage). The 500 W specification at a ten percent duty cycle corresponds to 50 W, continuous (assuming large battery storage). Consequently, the total power requirement for the main communications system is 320 watts at 24V DC (e.g. 13.33 amperes at 24V DC).

b. Microwave Relay Sites

A power consumption of 24 watts, 100 percent of the time, at 12V DC is needed to support the power requirements for the microwave relay sites. The power system and the batteries must provide 24 watts throughout the year (2A at 12V DC).

c. Backup Power

The existing thermoelectric generators located at the sites may be used as the backup power supply to the main communications site, if necessary. Additionally, a rechargeable battery bank with a 48 hour reserve (96 hours for the microwave relay sites) should be included. [Ref.1]

d. Average Daily Power Requirement

The average daily power requirement for each system (power consumption x 24 hours) is as follows. The main

communications system requires 7.68 kWh/day, while the microwave relay system requires 0.576 kWh/day.

Allowing for total system losses of 30 percent [Ref.2], for the charging and discharging of batteries above freezing temperatures, boosts the power requirements up to 10.97 kWh/day and 0.823 kWh/day for the main communications system and the microwave relay system respectively.

2. Reliability

The system must have the high reliability and long lifetime typical of military applications. This is due to the nature of the application for this power system design. The Coastal Voice Distress Network is an important part of the U.S. Coast Guard's search and rescue organization in the Alaskan region. It is a necessity for the safety of the ships and personnel that operate in that region.

According to a 1985 study, the basic requirement for any stand-alone power system to operate a remote telecommunications system [Ref.3] was a maximum unavailability of power, U, of:

$$U \approx 1.5x10^{-5} \qquad (2\text{-}1)$$

As shown in Equation 2-2, this amounts to a mean downtime of less than eight minutes per year.

$$1.5x10^{-5}x60\frac{min}{hour}x24\frac{hour}{day}x365\frac{day}{year}=7.884\frac{min}{year} \quad (2\text{-}2)$$

However, the goal of the power system will be to operate 24 hours a day, 365 days a year.

a. Accessibility

Most of the remote communications sites are in such isolated areas that the normal access to them is via helicopter. The helicopter flights are expensive and have the potential to be disastrous due to the inclemency of the weather. Consequently the power system reliability factor takes on additional importance.

b. Operation and Maintenance

The necessity for the communications system and power system to operate continuously demands that the reliability be high. Additionally, as the sites are isolated, a minimum of maintenance should be required. At the absolute maximum, the sites should only need repair and upkeep semiannually.

Reliability is of paramount importance for the power system designer. The prime power source must have a high degree of reliability. However, if the prime power source fails there must be a backup power supply that is continuously ready to pick up the communications load. This translates to designs in which the primary and backup power sources are fully integrated with each other, and each is

capable of supporting the full communications load. The remoteness of the sites will be overcome by the high reliability of the power system as a whole (prime power source and the backups).

3. Use of Existing Equipment

Existing equipment (power source, buildings, etc.) located at the remote sites should be utilized to the maximum extent possible. The main reason for this is to preclude having to bring more material to the remote site than is absolutely necessary. The second and seemingly overriding reason to exploit the existing equipment at the sites is to save money.

It is desirable to utilize the same power system for both the main communications sites and the microwave relay sites with respect to the type of power system used and the equipment required at each site. Minimizing the uniqueness of each site will reduce development and maintenance costs. Otherwise there will have to be a specific evaluation of alternatives at each and every site. However, some sites may require a special power system design that is unique to that site.

4. Fuel

As most locations are extremely remote and inaccessible (most requiring helicopters to visit and inspect), the need to decrease the number of site visits is

high. Therefore, as much as possible, the fuel requirements for the power system should be kept to a minimum by making use of the natural energy available at the sites. This can occur by developing and designing reliable hybrid power systems capable of utilizing available energy at these sites. These hybrid systems could incorporate wind power, solar power, geothermal, and hydro power, if possible, thereby minimizing the use of fuel for the thermoelectric generator systems.

III. THERMOELECTRIC GENERATOR

The current source of primary power at remote communications sites in Alaska is a thermoelectric generator. Thermoelectric generators have many drawbacks, with low efficiency being chief among them.

Though the existing communications equipment at the remote sites is being replaced by enhanced equipment, the increased power requirements at the sites must continue to be satisfied. Two questions need to be answered. Should thermoelectric generators continue as the primary power source at the remote communications sites? If thermoelectric generators are not used, which alternative power system(s) should be used? The first question is answered in this chapter, while the second will be answered in the next four chapters.

A. GENERAL

Thermoelectric generators exploit the phenomenon that current is produced when two dissimilar metals are joined in a closed circuit and the two junctions are maintained at different temperatures. This is the same precept employed in thermocouples, though thermocouples are used for measuring a temperature difference.

The primary role of a thermoelectric generator is nearly always for providing power to telecommunications and other

remote applications loads. It has virtually no other functions. [Ref.4] Thermoelectric generators are used in military and civilian remote applications, such as cathodic protection of pipelines, automatic weather stations, and signal lights. Thermoelectric generators operate in support of loads between approximately ten watts and one kilowatt.

Thermoelectric generators incorporate a bank of series-wired dissimilar metal junctions. When heated, to create a temperature gradient, these junctions exhibit an electromotive force by a principle attributed to Thomas Seebeck, reported in 1821. Electron energy levels are raised and lowered at the hot and cold junctions respectively. Many junctions are required to provide the nominal 24V or 48V DC voltage demanded for most telecommunications applications. [Ref.5:pp.135-143]

As illustrated in Figure 3-1, contemporary thermoelectric devices consist of two semiconductor materials, P-type and N-type. The semiconductor legs, connected electrically in series and thermally in parallel, are bonded to hot and cold junctions (shoes). The heat input at the hot shoe is partially removed at the cold shoe with the variance converted into electricity. The difference in the electric polarity between the P and N elements causes electric current to flow in opposite directions. In the P-type material the hole flow is in the same direction as the thermal gradient (from the hot to the cold junction). However, the electron flow is in the direction of the thermal gradient in the N-type material. A

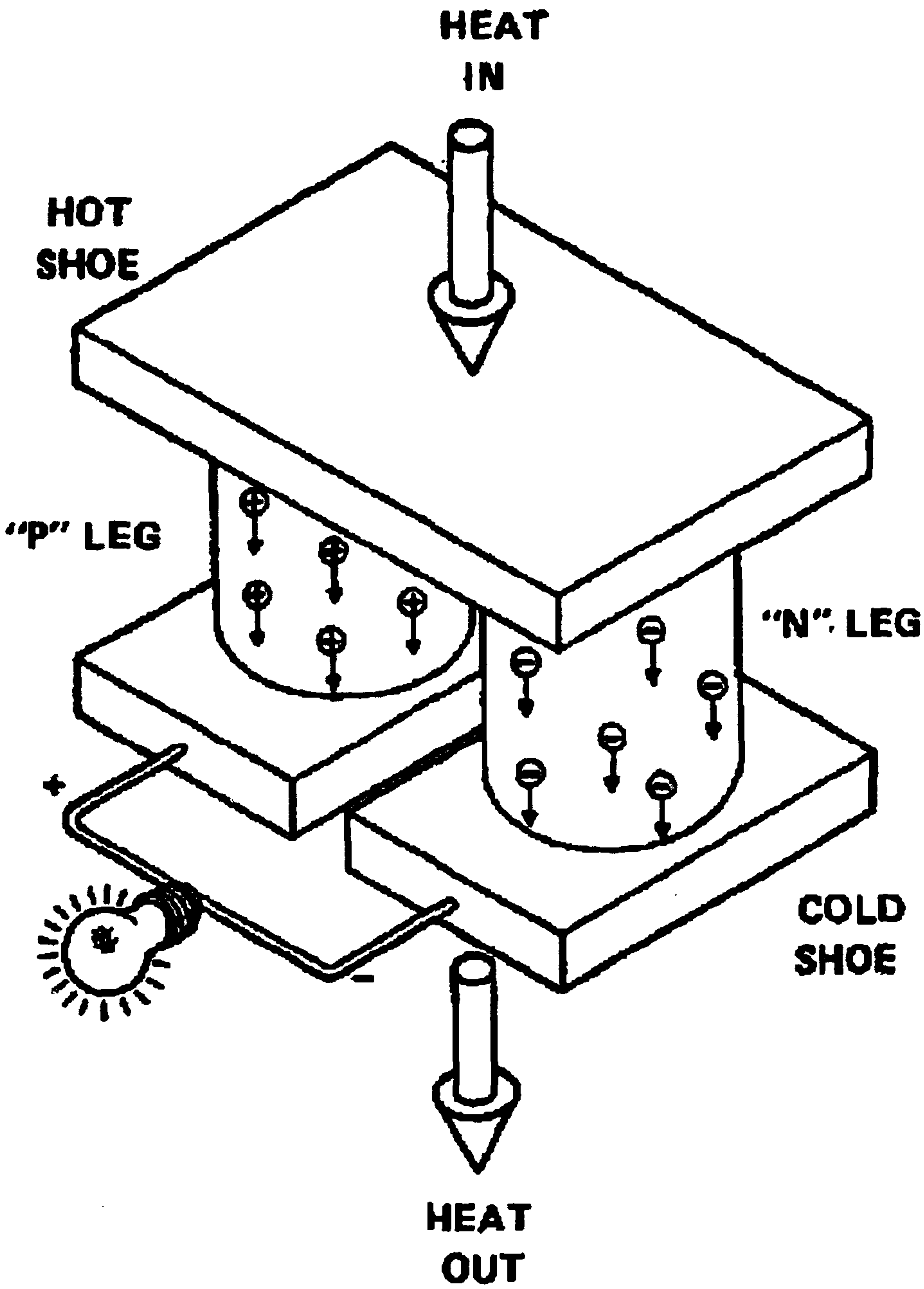

Figure 3-1. Operating Principle of Thermoelectric Conversion [Ref.6:p.89]

voltage is developed between the cold shoes due to the thermally driven flow of electrons. Current may flow through an external load connected between the P and N elements at the cold junction. Individual couples can be connected in an external series-parallel circuit to provide protection against open-circuits. [Ref.6:pp.89-90]

B. DEVELOPMENT AND HISTORY

Thermoelectric generators have been operated with solar, fossil fuel, radioisotope, and reactor heat sources. In 1954, Maria Telkes built a solar concentrator which generated 0.15 watts of power at an efficiency of approximately three percent. This was one of the first successful attempts at thermoelectric power production.

Fossil-fuelled thermoelectric generators were developed simultaneously in Russia and in the United States. The U.S. group first designed a thermocouple-powered gas-furnace safety valve. They later developed a series of small generators for use in remote locations. [Ref.5:p.173]

Many materials have been examined for use as thermoelements. The junction material most often used is lead telluride (PbTe). Among others are aluminum telluride (Al_2Te_3), gallium telluride (Ga_2Te_3), uranium telluride (UTe_2), and lately silicon germanium (SiGe). Telluride based thermoelectric converters are highly reliable. However, they are limited to low operating temperatures, below approximately

900°K. Silicon germanium converters can operate at much higher temperatures and have been reliably tested at temperatures above 1300°K. Higher efficiencies are possible with higher operating temperatures. Figure 3-2 is an illustration of a dimensionless figure of merit for several common thermoelectric junction materials. The figure shows that SiGe alloys can operate with nearly the same efficiency as PbTe alloys, although at a much higher operating temperature. It is expected that gains of 50 percent will be made in the figure of merit for SiGe alloys. Current space applications use silicon germanium alloys. [Ref.6:p.92] Theoretical efficiencies of up to ten percent have been calculated for binary compounds used in thermoelectric generators. [Ref.7:p.30]

Small thermoelectric generators have been successfully fuelled and operated using the heat of decaying nuclear isotopes [Ref.8:p.694]. The use of these radioisotopes can result in a generator that is able to be operated for extremely long periods of time (depending on the half-life of the radioisotope fuel) without maintenance, repair or visits. [Ref.4] However, the use of nuclear isotopes is a costly option. Additionally, there are the anxieties associated with the use of potentially hazardous radioactive materials (environmental concerns, storage, disposal, etc.).

As stated above, the space industry used thermoelectric (heat to electric power) conversion systems to power

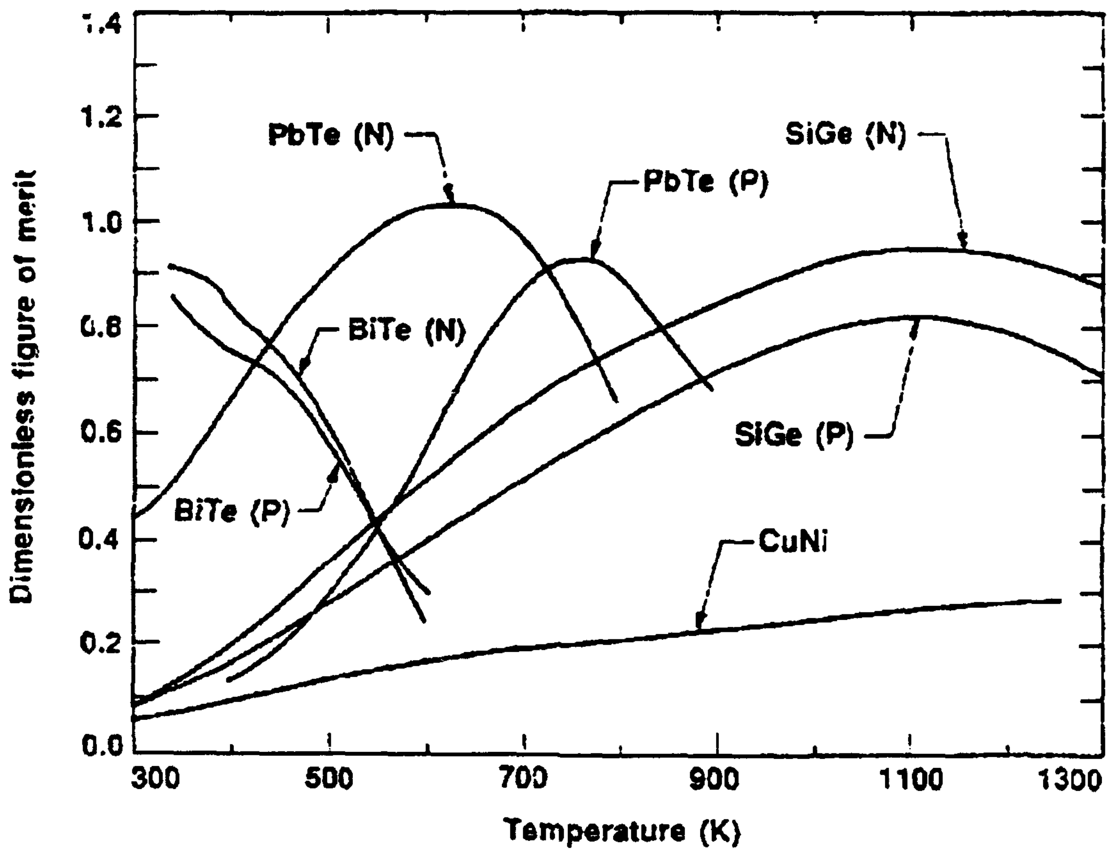

Figure 3-2. Dimensionless Figure of Merit [Ref.9:p.368]

satellites. The GPHS-RTG (General Purpose Heat Source Radioisotope Thermoelectric Generator) was constructed with 572 individual silicon germanium (SiGe) thermoelectric elements. It was developed to produce electric power for the Galileo and Ulysses spacecraft. A basic thermoelectric converter module is illustrated in Figure 3-3. Figure 3-4 shows a cutaway view of the major components of the GPHS-RTG that is capable of delivering greater than 285 watts electric. [Ref.9:pp.437-440]

C. ADVANTAGES

The inherent dependability of a thermoelectric generator allows it to be considered as a stand-alone power source. For some applications thermoelectric generators may be employed without either a back-up or secondary batteries. [Ref.4]

Semiconductor materials are used in modern thermoelectric generators. Since they are solid-state devices, their primary advantage is that they have no moving parts. Consequently, they need little maintenance. They can also operate from virtually any heat source, though the heat source does require maintenance. However, gas fired burners need less maintenance (nominally limited to once per year) than liquid fuelled burners. Consequently, propane delivery is the only activity forcing site visits to a thermoelectric power system. The thermoelectric generators located at the remote sites in Alaska utilize propane as the combustion material.

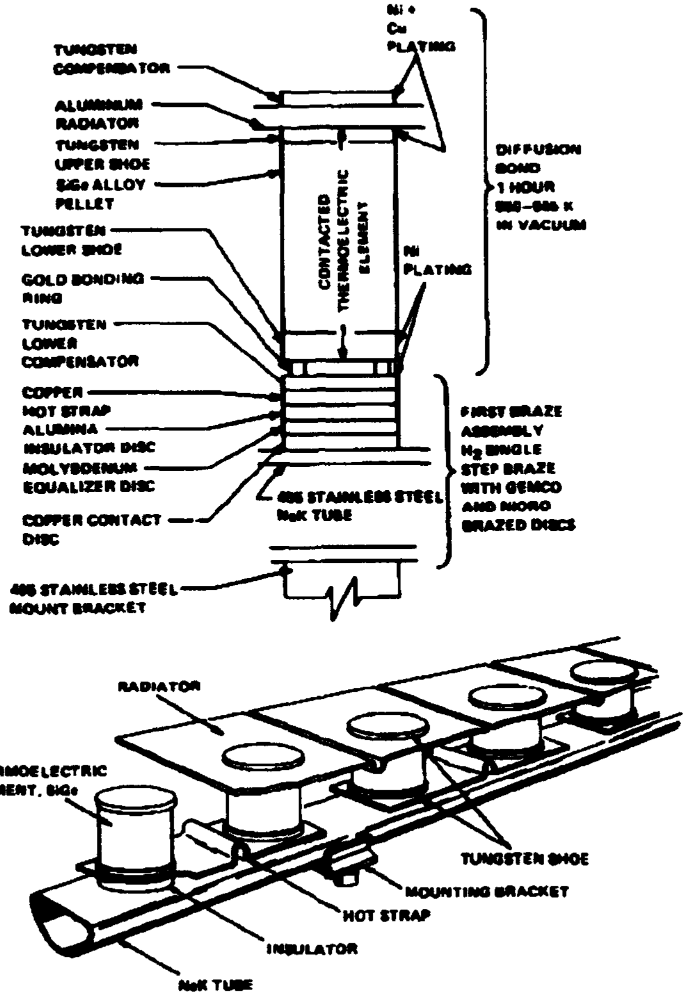

Figure 3-3. Basic Thermoelectric Module [Ref.6:p.166]

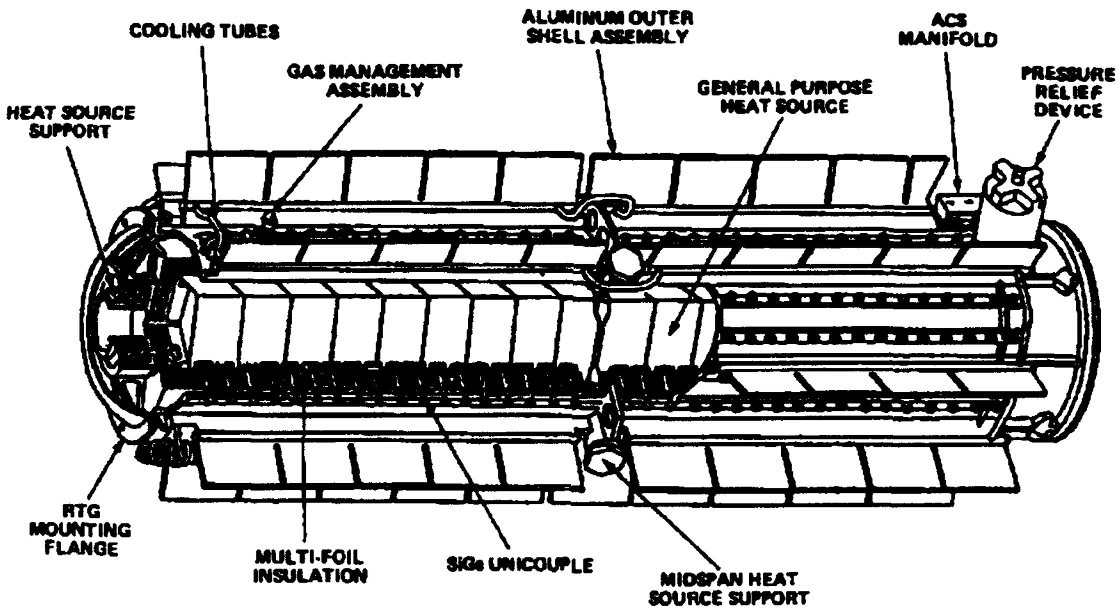

Figure 3-4. General Purpose Heat Source Radioisotope Thermoelectric Generator [Ref.9:p.439]

D. DISADVANTAGES

The biggest disadvantage to the utilization of a thermoelectric generator is its high cost of operation (cost per watt). Besides the heavy first cost, the thermal efficiency is quite low (approximately five percent), especially when compared with the use of internal combustion engines. This poor thermal efficiency commands a heavy fuel consumption in proportion to the electrical energy output (two and one half to three and one half kilograms of propane per kilowatt hour). With respect to the Coast Guard application, the operating costs are increased due to the necessity of resupplying the fuel by expensive helicopter transport.

E. DECISION

Thermoelectric generators should not be utilized as the primary power supply for the remote communications sites in Alaska. As the new communications equipment demands additional power to operate, additional larger quantities of propane would need to be transported to the sites. Combined with the poor thermal efficiency of the thermoelectric generator, the additional propane requirements would require more frequent helicopter flights to the remote sites. The high cost of transporting the propane and the danger of using helicopters in the inclement weather also adds to the list of reasons not to use thermoelectric generators as the primary power source in this application. However, thermoelectric

generators remain a viable primary power supply alternative for other applications.

In spite of not being recommended as the primary power source for the Coast Guard application, thermoelectric generators would make ideal backups to primary power sources, due to their high reliability and their ability to be started automatically. Since most sites already have in place a thermoelectric generator that was used to provide the power for the existing communications site, the use of the existing thermoelectric generators as a backup system would be easily accomplished to compliment the hybrid power system.

When used as a backup power supply, thermoelectric generators would remain dormant for long periods of time, thereby minimizing operating costs and fuel consumption. This would not affect their performance characteristics, since thermoelectric generators do not require routine operation to keep them in good working condition.

IV. OVERVIEW OF ALTERNATIVE POWER SUPPLIES

Having established the requirements and constraints of the remote communications stations and that a thermoelectric generator only system is impractical, the feasibility of using alternative power sources can now be examined. The first step is to evaluate the alternative power supplies by examining the advantages and disadvantages of each with respect to whether or not it can be used as a stand-alone prime power source for a remote communications station. The second step is to determine whether it can be used for the specific Coast Guard application.

In Chapter III, the following question was asked: If thermoelectric generators are not used, which alternative power system(s) should be used? The answer to this question lies in shifting, at least in part, from the use of thermoelectric generators as the sole source of power to the use of an alternative source. Among the possible alternatives are photovoltaic (solar cell) power, hydroelectric power, diesel generator power, fuel cells, and wind generation.

A. GENERAL

The difficulty of reliably supplying low levels of power (typically less than one and one half kilowatts) is one of the most significant limitations to the utilization of

telecommunications in remote areas. This is of great importance with respect to search and rescue planning and execution, as the United States Coast Guard needs communications coverage in even the most remote areas to ensure the safety of people, ships and aircraft.

Until recently (the last ten to twenty years), there were few alternatives remote power system choices. These expensive and less than ideal choices frequently proved uneconomical to provide and maintain. Human intervention was required in virtually all the conventional power options. Additionally, the provision of fuel supplies at frequent intervals often introduced an unacceptable cost overhead to the remote power system application. [Ref.4]

In the last twenty years, new alternative sources of power have begun to be exploited. Research and development of the utilization of "free" and renewable energy resources has increased the likelihood of power system applications requiring no fuel and limited maintenance. Energy efficient low-powered electronics coupled with an economical and reliable power source presents an attractive prospect for remote telecommunications use. Reliable and economical power source technology is a critical element of remote telecommunications operation.

Over eight years ago the International Telegraph and Telephone Consultative Committee (CCITT) of the International Telecommunications Union (ITU), Special Autonomous Working

Group No. 4 (GAS 4), produced a study entitled "Primary Sources of Energy for the Power Supply of Remote Telecommunications Systems."[Ref.3] This document defined the basic requirements for autonomous power supplies and reviewed a variety of power system alternatives.

B. OPTIONS CONSIDERED

1. General Considerations

The GAS 4 study considered systems deriving their power from the primary energy resources shown in Table 4-1 on the following page and specified the advantages and disadvantages for each.

The study also evaluated energy sources such as coal, wood, geothermal and radioactivity. However, the study determined that these supply options should not be considered with respect to power supplies for remote communications, as they are impractical or uneconomical.

Figure 4-1 illustrates the alternative power systems that could be deemed practical and feasible. Nevertheless, one system is not necessarily economically or operationally superior to the others in all respects.

The power system designer must consider several primary factors when comparing the alternatives.

TABLE 4-1. ENERGY SOURCES [adapted from REF.4]

SOURCE	ADVANTAGES	DISADVANTAGES	ENERGY STORAGE
Liquid Fuels	Practical	Non-renewable, increasing price	Not required
Gaseous Fuels	----	Non-renewable, explosion hazard, transport costly	Not required
Wind power	Free, inexhaustible	Problems with clam winds	Required
Solar power	Free, inexhaustible	Costly, dirt and dust problems	Required
Hydro-power	No fuel costs	Requires a suitable stream	Required
Hydrogen	Clean	Expensive, explosion hazard, storage/transport costly	Not required

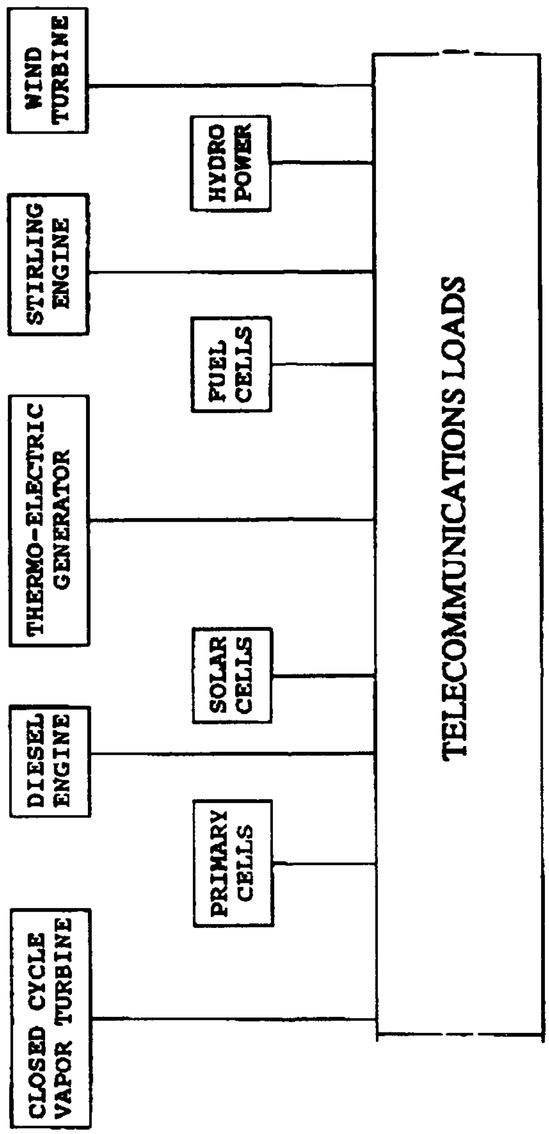

Figure 4-1. Power Supply Options [adapted from Ref.4]

- The availability of the energy resource.
- The relative costs of the power system alternatives.
- The scale of the system.

Conventional fossil fuelled systems (diesel generator, thermoelectric generator, ...) may be utilized whenever access to the sites is uncomplicated and or inexpensive. However, if the access to the site is extremely difficult and if the remoteness of the site precludes simple fuel supply routes and delivery, then other options must be considered. Among the other options are wind turbine and photovoltaic power, as long as wind and solar energy are available.

The scale of the system is important, since some alternatives are better suited for supplying large loads while others are suited for low power applications. For example, the maximum size of a thermoelectric generator is effectively limited to approximately one kilowatt because of its poor thermal to electric conversion efficiency and its large initial and high operating costs. On the other hand, the minimum size of a diesel system is approximately 2.5 kilowatts. [Ref.4] The limitations of scale can be diminished by using a supplementary system. Differences between the output and the load could be dealt with through the use of secondary storage batteries. However, this would increase both the complexity and the cost of the system.

The expense of the entire system is another factor to consider in the power system decision. Although the primary power supply is usually only a relatively small part of the total cost of the system, the high reliability demanded of remote telecommunications often makes the total system costly and complex. The total system may include components such as secondary battery storage, alarm systems, environmental protection, back-up systems, etc.

Obviously no single system is the best in all areas of consideration. There is no ideal power source for the remote communications application. Each option has advantages and disadvantages with respect to the application. The final choice has to be a compromise. In some cases the use of a hybrid system can improve reliability and/or reduce costs. However, the hybrid system will be a more complex system.

2. Diesel Generator

A diesel engine is an internal-combustion heat engine that operates on a modification of the thermal cycle proposed by Doctor Rudolph Diesel in the late 1800s. Diesel engines compress air so that its high temperature ignites the fuel when it is injected. It is the high compression ratios that makes possible the high thermal efficiency for which the diesel engine is noted. Developments in the 1980s raised the thermal efficiencies of diesels to nearly fifty percent.

The diesel engine is the most well-developed power technology available. Diesels power approximately eighty percent of all ships, trucks and locomotives. Consequently, diesels are the yardstick against which all other power sources must be judged.

As specified by the GAS 4 study [Ref.3], it is essential to utilize three diesels, operating in parallel, to guarantee the requisite reliability and availability. Complicated controllers to automatically shut down a malfunctioning engine, thereby preventing destructive failures, would also be a necessity. [Ref.4]

The most efficient operation occurs when a diesel engine is fully loaded. However, the smallest commercially available diesels are approximately two kilowatts and engines of five kilowatts or more are customarily used as they are more robust and reliable. Consequently the diesel engine must operate at low part load or have artificial loads when utilized for low power telecommunications applications. Continuous operation at low part load is unsatisfactory as engine efficiency is decreased and fuel injectors have an increased propensity towards being clogged. As an alternative to part load or artificial load operation, the diesel system could be used to charge secondary batteries for a few hours per day, with the batteries providing a continuous supply to the loads. [Ref.4 and Ref.10:p.332] The drawback to this strategy is that diesels have poor cold-starting

characteristics which would be detrimental to the cold weather operation in Alaska. Additionally, diesel fuel will freeze in extremely cold weather unless it is chemically treated.

The drawbacks to diesel utilization for remote applications are the frequent maintenance requirements and substantial parts inventory. Consequently, diesel engines have high operation and maintenance costs. Additionally, whenever access to a site is a problem, fuel transport will be costly (especially for helicopter transport). With respect to remote communications site operation, the liabilities of diesel engine utilization outweigh the benefits. Therefore, the diesel engine should be eliminated as an option.

3. Closed Cycle Vapor Turbine (CCVT)

The Closed Cycle Vapor Turbine (CCVT) uses the well-known Rankine Cycle. This is a closed cycle which entails the phase change of the working fluid in order to convert heat into work. Unlike a steam turbine, the working fluid of the CCVT is a heavy organic fluid (hydro-carbons or fluoro-carbons). Like thermoelectric generators, the CCVT needs heat to operate. This heat can be provided by liquid or gas fuelled burners. [Ref.11:pp.53-55]

The CCVT, like the thermoelectric generator, finds its main application in powering remote telecommunications equipment. It is valuable in this situation as it is highly reliable, needs little maintenance, and effectively meets

continuous power demands in the 100 to 4,000 watt range. [Ref.4]

Closed Cycle Vapor Turbines have similar advantages and disadvantages as thermoelectric generators. The CCVT operates in a slightly larger power range than a thermoelectric generator and has a somewhat higher thermal efficiency (from seven to ten percent versus approximately five percent). Several disadvantages are connected with the use of organic fluids. Among them are a relatively high cost, toxicity and flammability.

Like thermoelectric generators, Closed Cycle Vapor Turbines are reliable enough for stand-alone operation. A CCVT could be utilized in applications that require more power than a thermoelectric generator can provide or are too remote or require too little power to justify the costs associated with the use of a diesel engine. [Ref.4]

Closed Cycle Vapor Turbines are eliminated as an option for the remote communications site primary power source for the same reasons that thermoelectric generators were eliminated (high operating costs and the necessity of helicopter fuel delivery). However, like thermoelectric generators, CCVTs may be ideal for backing up a solar or wind power system as they are reliable, have the ability to be started automatically, and can be dormant for long periods of time with no detrimental affects to their performance characteristics.

4. Stirling Engine

The Stirling engine is a closed regenerative cycle heat engine that has its roots in the hot-air engine invented by Doctor Robert Stirling in 1816. The Stirling engine has many favorable characteristics which have led to considerable research and development in recent history. [Ref.12:p.15]

- The exhaust gases are relatively clean and cool and consequently produce minimal pollution.
- The energy source required for heating may be of almost any form. Stirling engines have been run on a variety of liquid and solid fuels as well as on solar energy.
- Low fuel consumption and relatively high efficiency.
- Mechanically simple with low maintenance requirements.
- Reliability comparable to other options.

The Stirling engine develops a work output from a thermal input. As an enclosed gas is displaced from a cold space to a hot space, the pressure of the gas increases. The pressure increase provides power if it acts on a moving piston. The gas is then shunted back to the cold space and the cycle is repeated. Stirling engines have regenerators that prevent the loss of heat between cycles. As a thermodynamic cycle, it is one of the most efficient. A variety of Stirling engines have been built with efficiencies exceeding those of diesel engines.

As an unattended remote power generator for communications applications, the Stirling engine has excellent

potential. Stirling engines are mechanically simple and relatively slow-revving with few moving parts. Additionally, unlike a CCVT or a thermoelectric generator, they have the promise to be fuel efficient (better than diesels, as they have much better part load characteristics). They also have multi-fuel capability and can conceivably even be solar heated (a solar heated system was tested with an efficiency of 33 percent).

Unfortunately, Stirling engines do have some drawbacks. Research and applications development has not been readily forthcoming, especially in applications where diesels are the power providers, because the diesel has a better power-weight ratio and power-size ratio. However, the ratios are usually not important considerations for stationary remote power applications. [Ref.4] Another significant drawback is that Stirling engines are more complex than traditional heat engines.

This is a technology that is potentially well-suited to reliable, autonomous and long-term power generation in the entire range of interest for remote telecommunications. It seems to be only a matter of time before commercially available Stirling engines are ready for remote communications power supply systems. [Ref.4]

5. Fuel Cells

A fuel cell converts chemical energy into electricity. Although the electrochemical principles are the same as for batteries, the difference is that the fuel in fuel cells is external to the conversion device itself.

An individual fuel cell consists of two electrodes (anode and cathode) separated by an electrolyte. A chemical compound is released in the electrolyte as fuel and oxygen are consumed at the anode and cathode respectively. A flow of electrons takes place between the anode and the cathode if they are connected by an external circuit. A fuel cell battery consists of individual cells connected in series, in parallel, or in series-parallel. Each individual cell is theoretically capable of producing approximately one volt. [Ref.5:pp.39-48]

Fuel cells were given publicity through their use in providing electric power for the Apollo mission spacecraft to the moon. They are also used as the primary electric power source aboard the space shuttle (three 12 kWh cells are utilized on each orbiter). They are much more efficient in the use of their fuels, hydrogen and oxygen, than would be the case if the fuels were simply burned and the heat used by an engine or turbine to drive the electrical generator.

Fuel cell technology seems well suited to telecommunications remote power applications. Unfortunately,

it continues to languish in the research and development phase rather than in the test and operational stage.

There are some significant advantages to the use of fuel cells. Efficiencies as high as eighty percent have been demonstrated. This is far superior to any other fuel burning electricity generator. As there are no primary mechanical components, it has the potential to be an extremely reliable, long-lasting and autonomous power supply. [Ref.4]

Unfortunately, there are disadvantages to fuel cell use. As previously mentioned, fuel cells produce only about one volt per cell. It is clear that at least 24 and possibly 48 cells are needed for most telecommunications applications. Additionally, fuel cells are more complex than traditional battery cells (pumps, circulators, coolers and temperature controls are needed for their operation). The utilization of fuel cells is too complex for small applications. Hence they would probably be better-suited to supplying continuous power demands in the kilowatt range. The high cost of existing fuel cells is also a disadvantage. Fuel cells are not "normal" off-the-shelf products, although they can be special-ordered at a high price. [Ref.4]

Another series of disadvantages stems from the use of hydrogen as the fuel in a fuel cell.

- Hydrogen is difficult and costly to transport.
- Hydrogen is not as readily available as other fuels, i.e., propane or diesel fuel.

- Hydrogen is an extremely dangerous material, i.e., it is a highly flammable and explosive risk.

Fuel cells seem unlikely to become a practical solution until they can be manufactured economically to use inexpensive fuels, or an economical means to store or generate hydrogen is developed.

6. Primary Cells

Primary cells are mentioned to provide a thorough review of potential alternatives, rather than as a potential power source for the Coast Guard application. Their high cost and limited lifetime severely restricts them to applications with power demands typically less than one watt.

Primary cells are similar to the basic flashlight battery in which prepacked electrochemicals react to produce *an electro-magnetic force (emf).* Primary cells are used until they are exhausted. The cell is then discarded and replaced by a fresh one. [Ref.4]

Costs for this source are very high, as the lifetime of a cell is relatively short. The operating life for the cells ranges from 0.5 to 36 months. Other disadvantages of primary cells are the relatively short shelf life and environmental considerations due to the corrosive nature of the chemicals within the cells.

7. Hydroelectric Power

Waterpower, which is continually resupplied by the sun, is more concentrated than solar power and can be stored in large reservoirs. Hydroelectric conversion approaches eighty percent efficiency, whereas efficiency in coal or fuel oil systems is approximately thirty-three percent. If efficiency alone determined the success of an energy system, hydroelectricity would rank at the very top. [Ref.13:pp.621-635]

Hydroelectric power is a technology with a single overriding requirement, the need for a suitable hydro-resource sufficiently near the point of use of the power. Hydropower is reliable, easily maintained, durable and long-lasting. However, it needs a suitable stream that neither freezes nor dries up, within approximately one kilometer of the telecommunications installation. [Ref.4] Such resources will be difficult to find, if they exist at all, in Alaska, at the Coast Guard sites.

Hydropower could be used in conjunction with another power supply to form a hybrid power system in some situations. For example, when atmospheric conditions limit the use of a photovoltaic system during the winter months and the hydropower source (a stream) dries up during the summer months.

The photovoltaic/hydro hybrid system was eliminated as an option due to the unavailability of substantial solar

energy in the winter months and the sub-zero weather causing all running water to freeze. [Ref.1] However, this is with respect to this Coast Guard application only. The photovoltaic/hydro hybrid system has potential as an option at other remote telecommunications applications.

8. Photovoltaic Systems

Photovoltaic technology is perhaps the best understood of the renewable energy options. It is rapidly becoming widely used as an option for telecommunications applications.

One of the main advantages of a photovoltaic system is that it involves a solid-state energy conversion process. Consequently, it has the potential of a long operational lifetime, and minimum maintenance requirements. Nonetheless, a significant liability applies to systems located at higher latitudes or in areas where there are atmospheric conditions that curb the energy output. This limitation forces the photovoltaic system to be excessively large in order to deliver the minimum power requirements to the system loads. [Ref.4]

If this limitation is a seasonal problem, then it may be mitigated through the use of a hybrid system. For example, using solar power as part of a hybrid system with an alternative, such as a thermoelectric generator or a wind turbine, producing the power during the winter season. The

cost of the alternative power supply is partially offset by the reduction in the size of the photovoltaic array required.

This technology is discussed in greater detail in Chapter V.

9. Wind Turbine Power Systems

As a power generating option, wind turbine electric power generating systems are among the most attractive of the renewable energy generation technologies. In their current form, wind-driven generators represent not a replacement for conventional sources, but rather a complement.

Wind-driven power systems represent a renewable technology which has rapidly evolved over the past decade, particularly in California. Since 1984, reliable micro-wind-turbines (typically rated at approximately fifty watts at a wind speed of ten meters per second) have gone into relatively high volume production. [Ref.4]

Wind turbines are an attractive fuel saving option. They may be used in conjunction with fossil-fuelled generators, such as thermoelectric generators and CCVTs, or they may form part of a hybrid system. The marginal cost of adding a wind-driven generator to a system having a fossil fuel primary power source and secondary storage batteries can be quite small, yet its capacity for saving fuel is great. When used as part of a photovoltaic and wind hybrid power system, a wind-driven generator will preclude the need for a

grossly oversized photovoltaic array. While water mills suffered from the disadvantage of limited locations, a much greater freedom of choice exists for the location of wind systems. Wind turbines are discussed in further detail in Chapter VI.

C. SUMMARY

Of the nine power system alternatives presented in this chapter, two stand-alone options remain viable as potential replacements to the existing thermoelectric generators at the remote telecommunications sites in Alaska. The two remaining system options are a photovoltaic system and a wind-driven turbine generator system. They will be discussed in the following two chapters. A hybrid combination of photovoltaic and wind turbine power is discussed in Chapter VIII.

With respect to the remote communications sites in the Alaska application, all of the fossil-fuelled alternatives were eliminated from consideration due to the fuel supply requirements and the hazards associated with helicopter delivery. The hydroelectric power option was discarded due to the freezing temperatures and the distances from the sites to suitable water sources. A primary cell system alternative was abandoned because of the relatively short shelf life of the cells. A fuel cell option, though having by far the highest efficiency of any of the evaluated systems, was rejected

because the technology is costly, not easily transportable and has excessive explosive risks.

It is again worth mentioning that these options were rejected based upon the specific Coast Guard application. These options could be re-evaluated for a different application with far different results.

V. PHOTOVOLTAIC SYSTEM

Ever since Prometheus stole the fire of heaven from the gods, virtually all the energy consumed by humans has come from the sun. Coal, oil, and natural gas are the residues of plants and animals, which originally derived all the energy for their development from solar radiation. Solar radiation also drives the earth's rain cycle, which powers modern hydroelectric generators, and large-scale atmosphere circulations provide the winds that have powered windmills for many centuries. [Ref.14:p.1]

A. FUNDAMENTAL ASPECTS OF SOLAR ENERGY

1. Historical Perspective

The earliest form of civilized use of solar energy dealt with man's home. "Solar tempered homes have existed since Neolithic times, when people crawled from their caves, rubbed the darkness from their eyes, and piled or pounded together their first structures." [Ref.15:p.5]

The sun was used as a source of military power over 2200 years ago. According to legend, Archimedes set fire to Roman ships attacking Syracuse, lining up a thousand soldiers with highly-polished shields. The rays of the sun were reflected onto the sails of attacking ships. The Roman ships burned when the sails burst into flame, and Syracuse was saved. [Ref.7:p.1]

Serious studies of the effects and potential of the sun began in the 18th Century, when the French chemist, Lavoisier, designed and built a solar furnace to concentrate

and focus the sun's rays for his research and experiments. In 1774, Joseph Priestly discovered Oxygen when he concentrated the sun's rays onto mercuric oxide and collected the resultant gas produced by the heating process. In Paris, in 1878, sunlight was concentrated on a steam boiler that operated a steam engine to run a printing press. [Ref.14:p.524 and Ref.16:p.18]

From 1902 to 1918, H.E. Willsie and John Boyle, Jr., constructed and tested four solar engines throughout the United States. Though a commercial failure, their engines were a technical success. [Ref.7:p.1] By the year 1930, a rocket specialist, Dr. Robert Goddard, had applied for five patents on solar devices to be used on his project to send a rocket to the moon. [Ref.7:pp.13-24 and Ref.16:p.22]

In more recent U.S. history, solar water heating was a thriving business between 1930 and 1950. However, it took the billions of dollars in space research and development, in addition to the need to power satellites in space using the sun's energy, to significantly advance the use of solar energy.

2. Solar Cell Development

Solar cells are two-terminal, solid-state semiconductor devices that convert solar energy into electrical energy. [Ref.17:p.3.0-1] The photovoltaic effect-the physical phenomenon that converts the sunlight into

electrical energy- upon which solar cells depend for their operation, was first observed and reported in 1839, by Edmund Becquerel, a French physicist. He observed that a light-dependent voltage existed between two electrodes immersed in an electrolyte. In the 1870s the effect was observed in the solid Selenium, by Adams and Day. Photocells made of Selenium were developed in the 1880s. They exhibited efficiencies of up to two percent when converting light to electricity. [Ref.18:p.24-1 and Ref.19:p.2]

In the 1920s and 1930s, Lange, Schottky and Grondahl pioneered work on photocells made of Selenium and cuprous oxide. Bell Telephone Laboratories began theoretical research on the photovoltaic effect in the 1930s. In the 1940s, experiments with silicon accelerated development of electrical devices using semiconductors. In 1954, the first practical Silicon solar cell was produced, capable of converting six percent of the incident solar energy to electrical energy.

Innovations by Czochralski - The Czochralski Method - in pure crystal growing helped overcome a stumbling block in the development of photocell production. Advances by Fuller and Ditzenberger in high-temperature vapor diffusion for p-n junction formation brought forth the necessary technology for successful semiconductor devices with higher efficiencies. [Ref.16:p.1.2-1]

Solar cells are devices in which sunlight releases electric charges so they can move freely in a semiconductor

and ultimately flow through an electric load. The first silicon solar cells were approximately three centimeter diameter circular wafers, resulting from the maximum diameter crystal that could be grown with existing technology. Conversion efficiency was between six and ten percent.

Breakthroughs in the fabrication process improved understanding of cell operation theory, and improvements in designs led to higher cell efficiencies. A terrestrial photovoltaic (PV) cell with an energy conversion efficiency of almost 14 percent was produced by the Hoffman Electronics Corporation in 1958 [Ref.20:pp.120-124] Around the same time, Bell Telephone tested a PV array for rural telephone transmission. Although the array performed as expected, it was determined to be more costly than utility or conventional battery power. However, "... it was then apparent that the direct conversion of solar radiation into electrical energy by means of the photovoltaic effect would someday prove to be a useful source of electrical power."[Ref.5:p.1]

While the solar cell was first considered only for terrestrial applications, their advantages of light weight and small size found use in the U.S. space program. The successful operation in 1958 of a small solar cell array, powering the radio of the Vanguard space satellite, launched photovoltaic technology into a significant role in the U.S. space program. This array provided power for more than six years. [Ref.21:p.8]

Little progress was made in the development of more efficient solar cells in the ten-year period from 1961 to 1971. [Ref.17:p.1.2-1] In the late 1960s and early 1970s new photovoltaic compounds such as Gallium Arsenide (GaAs) and new anti-reflective coatings, made of tantalum pentoxide (Ta_2O_5), introduced new "high efficiency" cells with conversion efficiencies of up to 16 percent. [Ref.7:p.29 and Ref.17:p.1.2-2] These developments, coupled with the search for new and better energy sources - the energy crisis of the 1970s - reawakened interest in terrestrial applications for the solar cell. [Ref.19:p.2]

3. Solar Radiation

Much of the radiation striking the earth as short-wave radiation is reradiated as long-wave radiation. [Ref.22] This is the radiation of interest, as far as applications to solar energy systems are concerned.

The radiation intensity outside the earth's atmosphere, known as air mass zero (AM0) or the solar constant is approximately 1353 W/m^2 (the literature defines the solar constant with various values from 1368 W/m^2 to 1395 W/m^2). The solar constant is defined [Ref.23:p.6] as the rate at which energy is received upon a unit surface, perpendicular to the sun's direction, in free space at the earth's mean distance from the sun. This radiation embodies the visible and invisible portions of the solar spectrum. [Ref.24]

In the absence of the earth's atmosphere, the global distribution of sunshine would make all latitudes as sunny as any other latitude. However, the earth's atmosphere and weather patterns cause a significant modification in this distribution, such that the sunniest regions of the earth are concentrated in two distinct bands. These two latitude bands are from twenty to thirty degrees north and south latitude. These zones have an annual solar radiation average exceeding ninety percent. Insolation decreases both north and south of these two zones. [Ref.7:p.50]

Air mass one (AM1) is designated as the amount of radiation that reaches sea level on a clear day at high noon, with the sun directly overhead, where seventy percent of the solar radiation incident to the earth's atmosphere reaches the surface. The spectral irradiance of the sun at air mass zero and at air mass one is shown in Figure 5-1.

Sunlight varies in intensity due to changes in the sun's position (daily and seasonal), latitude and light diffusion due to atmospheric scattering. Diffuse sunlight (some of the scattered and reflected radiation) can account for up to 20 percent of the total radiation received by a horizontal surface. The actual amount of sunlight falling on a specific geographic location is called insolation. [Ref.25] The radiation that Alaska receives is approximately air mass six, AM6. The irradiance spectrum for an arbitrary air mass, AMK, may be estimated from the spectrums of AM0 and AM1 using

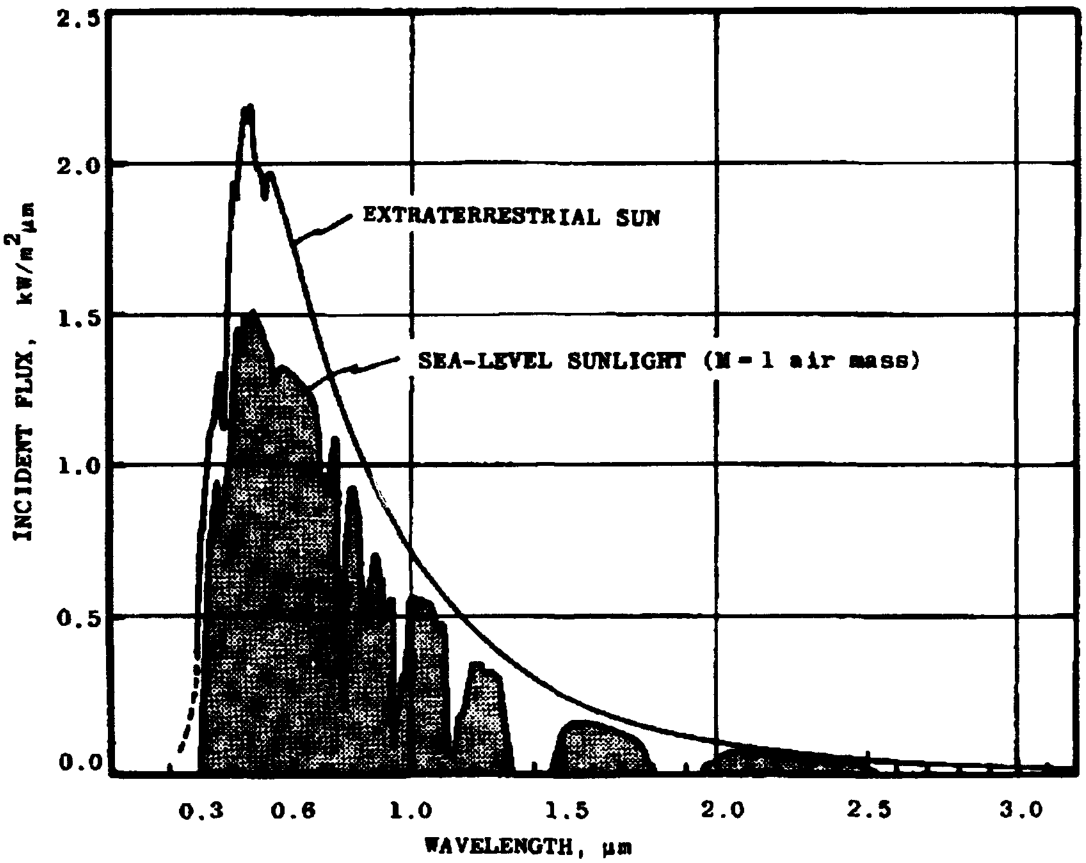

Figure 5-1. Solar Spectrum [Ref.7:p.42]

the equation shown below.

$$I_{AMK}(\lambda) = I_{AM0}(\lambda)\left(\frac{I_{AM1}(\lambda)}{I_{AM0}(\lambda)}\right)^{K^{0.678}} \tag{5-1}$$

where $I_{AMK}(\lambda)$ is the irradiance at air mass K, as a function of wavelength, λ. [Ref.26:p.22]

Attenuation takes into account that part of the sun's radiation that is reflected, scattered, and absorbed by heating air, dust, CO_2, and water vapor. [Ref.26:p.21] Sunlight undergoes a minimum of 30 percent attenuation, while traveling through the earth's atmosphere, before reaching the earth's surface.

Sunlight is measured in terms of power density. Power density is the amount of power crossing a given area expressed in terms of milliwatts per square centimeter (mW/cm^2) or kilowatts per square meter (kW/m^2). Power density is also referred to as irradiance or intensity.

All of these factors have to be taken into account when designing and locating a photovoltaic system. The importance of measuring solar radiation cannot be underestimated in designing an effective solar system. The physical practicality and economic justification for purchasing a solar collector are closely related to the solar radiation measurements at a given location. [Ref.16:p.29] The annual monthly solar radiation intensity characteristics for

specific geographical regions can be found in numerous sources for that purpose. Appendix B contains a sample listing of average monthly solar radiation intensities received at several locations.

The sun perpetually bathes the earth with pollution-free radiant energy, and is in essence an enormous thermonuclear generator. Accompanying harmful radioactive particles are mostly trapped in the earth's upper atmosphere. [Ref.27]

The amount of the sun's energy intercepted by earth is only a tiny fraction of the total released. A significant portion is lost in space due to reflection, absorption, diffusion, etc. However, in only 15 minutes the earth intercepts as much radiant energy from the sun as mankind consumes each year in the form of fossil fuels and nuclear energy. [Ref.27 and Ref.28]

B. THEORY OF SOLAR CELLS

1. General

Engineering of a solar cell power system must start with a thorough knowledge of the solar cell. The investigation must begin with a theory of operation. Various parameters must be tested, including: electrical quantities, efficiency and temperature effects. With these parameters in mind, the engineer must also consider cost and the type of solar cell needed for the application.

2. Theory of Operation

This section will present a brief discussion of solar cell operations. A detailed discussion of solar cell construction and operating characteristics is contained in *Solar Cells: Operating Principles, Technology, and System Applications* by Green [Ref.19] and the *Solar Cell Radiation Handbook* [Ref.29].

Photovoltaic conversion is a process of converting radiant energy into electric charge separations. The most commonly available solar cells are composed of crystalline Silicon. They are semiconductors with solid state characteristics that promote separation of charge and a resultant flow of electric current in an external circuit called the load. This load dissipates the power generated by the photovoltaic device. [Ref.30:pp.30-54]

When sunlight is incident on a semiconductor device, three things can happen. The energy of the photon passes through the cell, it is reflected or it is absorbed by the cell. The solar cell can only produce an electrical current from absorbed sunlight. This can only happen when the light hits an electron in the valence band with sufficient energy to cause an electron to be moved to the conduction band. When this happens, an electron-hole pair is generated (an electron boosted into the conduction band and a hole left in the valence band). [Ref.19:p.27]

The electron-hole pair, free to roam from one atom to the next, makes the photovoltaic effect possible. However, if there is no external mechanism present, the electrons will eventually lose their energy by collision and return to their valence positions. The net effect of the absorption process without an external forcing function is nothing more than a heating up of the semiconductor. [Ref.19:pp.27-30]

The mechanism used to prevent this is the potential barrier formed by the solar cell. This electric field is produced at the junction of N-type and P-type segments of the same material. The potential barrier or depletion region prevents electron-hole recombination by sweeping electrons from the p-region to the n-region. On the other hand, holes are forced from the n-region to the p-region. In the n-region electrons are termed majority carriers, while holes are the minority carrier. Conversely, holes are the majority carriers and electrons the minority carriers in the p-region. [Ref.19:p.31]

Since the barrier sweeps minority carriers across the junction, preventing majority carriers from crossing, minority carriers have a high probability of reaching the region surface. As illustrated in Figure 5-2, electrons reach the top surface in the n-region, while holes reach the rear surface, creating a voltage difference across the cell and generating a current through an external electrical load. [Ref.19:pp.29-34]

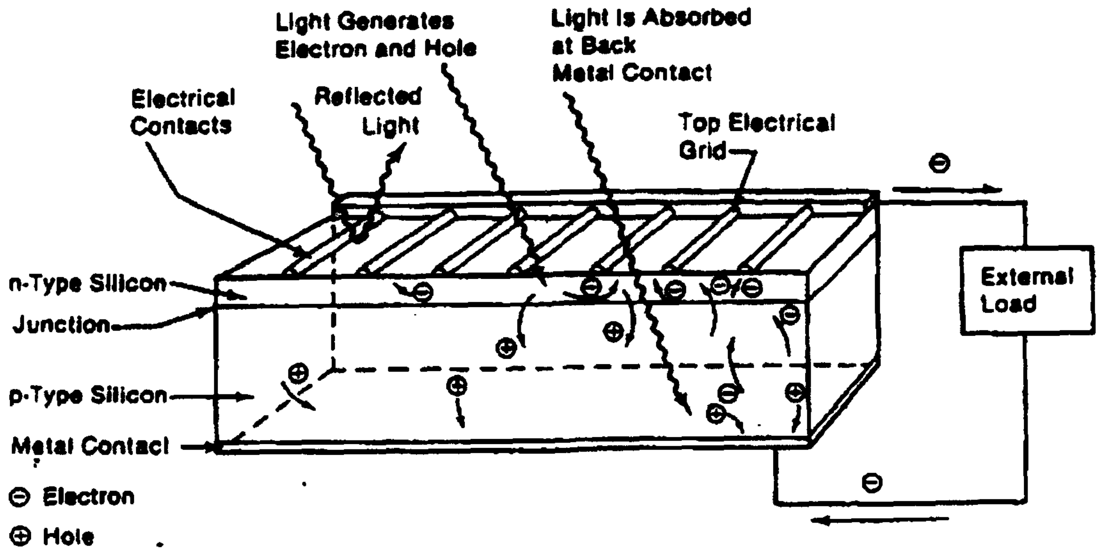

Figure 5-2. Generation of Current [Ref.31:p.14]

3. Efficiency

Most of the energy that reaches a photovoltaic cell in the form of sunlight is lost before it can be converted into electricity. The best photovoltaic devices have theoretical maximum efficiencies in the 20 to 28 percent range, while the practical limit is approximately two to three percent lower. [Ref.32:pp.922-926]

Solar cell energy conversion efficiency is the ratio of the power output to the power input. Cell efficiency is given by the equation:

$$\eta = \frac{P_{out}}{P_{\epsilon}} = \frac{V_{mp} I_{mp}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}} \qquad (5\text{-}2)$$

where

η= conversion efficiency,

P_{out}=electrical power output of the solar cell, and

P_{in}=power input or the total incident light power to the cell. [Ref.19:p.81]

Maximum efficiency, η_{max} occurs at the maximum power point (P_{mp}). Common commercial cell efficiencies are in the range of 12 to 16 percent.

Figure 5-3 shows typical current-voltage (I-V) and power-voltage (P-V) curves for a solar cell. A specific pair of voltages and currents will maximize P_{out}. P_{mp} is given by the equation

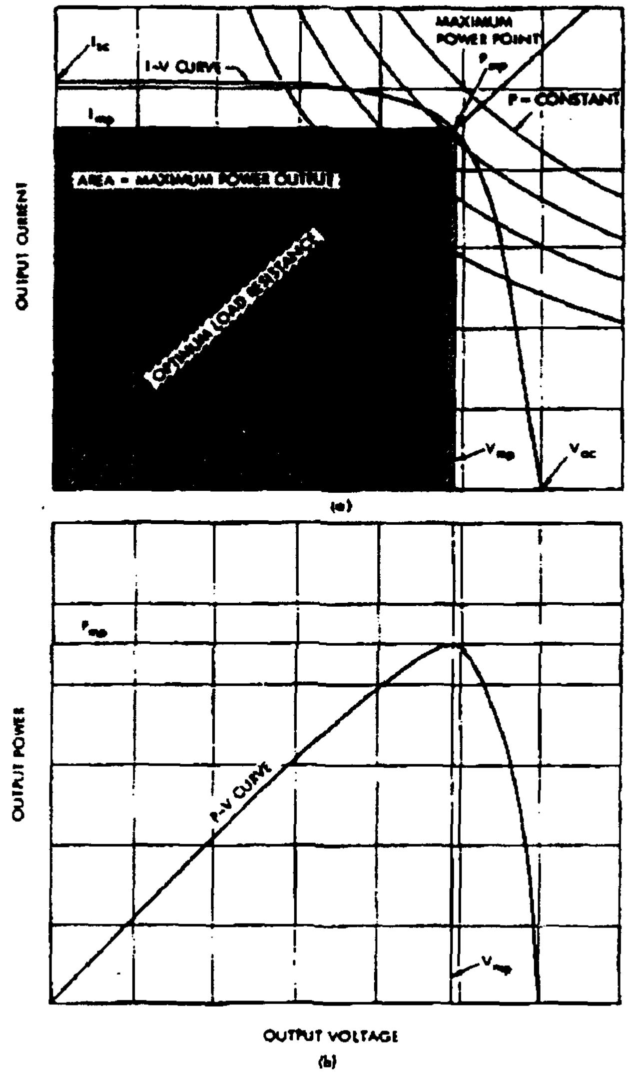

Figure 5-3. Characteristic I-V and P-V Curves [Ref.17:p.3-2.1]

$$P_{mp}=V_{mp}I_{mp} \tag{5-3}$$

where I_{mp} and V_{mp} are the current and voltage at the maximum power point, respectively. A solar cell operates at its maximum efficiency, η_{max}, when the maximum power output capability is utilized by an optimized load at a particular illumination intensity and cell operating temperature. As shown in Figure 5-3a, the intersection of the I-V curve and a constant power curve is not clearly distinguished. Thus, a P-V curve (Figure 5-3b) is produced to document the output power to output voltage relationship. [Ref.21:p.171]

The maximum solar cell efficiency depends on several different aspects of the solar cell. These are the solar cell internal construction, active area, specific material properties, photovoltaic junction characteristics, anti-reflective coating, surface texture, contact and grid configuration, illumination levels, cell operating temperature, particulate irradiation damage, and temperature cycling. Figure 5-4 shows the theoretical efficiency of different types of semiconductor materials used in solar cells. Notice that a GaAs solar cell has a higher efficiency than a Si cell.

Neglecting all other energy losses, the maximum efficiency is obtained for a band gap energy of approximately 1.5 electron-Volts (eV) for the solar radiation that exists

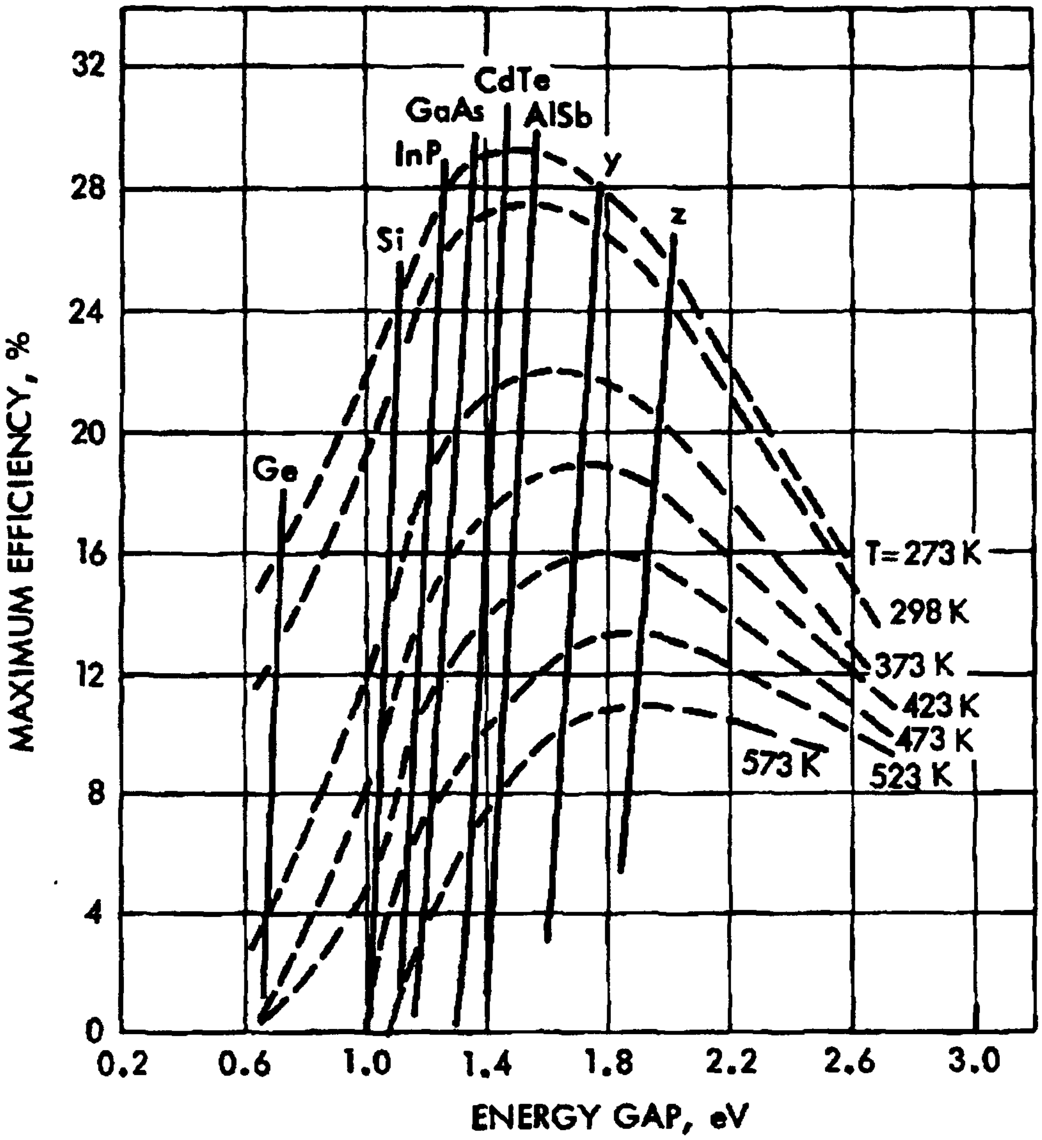

Figure 5-4. Maximum Efficiency As A Function Of Band Gap Energy [Ref. 29:p.1-32]

above the earth's atmosphere. This is illustrated in Figure 5-4. The greatest difference between silicon and the optimum material is approximately five percent, for the spectrum outside the earth's atmosphere. For terrestrial use in the Alaska region, the difference is almost negligible. Consequently, it is not necessary to switch to a different material other than silicon (i.e., GaAs). Other materials would be more costly and wouldn't provide a significant increase in benefit.

a. Effects of Increasing the Concentration Ratio

The purpose of a solar concentrator is to increase the sunlight intensity falling on the solar cell. While keeping other factors constant (i.e., cell temperature), changing the illumination intensity changes the cell's output characteristics. For example, by increasing the intensity, the cell's maximum power output and efficiency will be increased. An increase in efficiency means a decrease in the number of solar cells required to satisfy the same power requirements which in turn means a decrease in the size of the array and a substantial cost savings.

The increased sunlight intensity causes more electron-hole generations, which in turn increase the short-circuit current and increase, though not as much, the open-circuit voltage. These increases result in an increase in the maximum power output and solar cell efficiency. [Ref.21:p.173]

Figure 5-5 shows an I-V curve of a solar cell under three different illumination levels.

b. Effect of Temperature

In the above discussion, the solar cell operating temperature was assumed to be held at a constant temperature. However, if the intensity is increased, the cell's efficiency and power output will decrease, resulting from an increase in the cell's temperature. Current-voltage curves of a typical solar cell operating under different temperatures are illustrated in Figure 5-6. It should be noted that the power output of the solar cell decreases as the cell temperature increases. At a constant cell voltage the output current drops rapidly with increasing temperature.

4. Electrical Characteristics

a. I-V Curve

The current-voltage curve or I-V curve is used to describe the solar cell's electrical characteristics. From a typical I-V curve (Figures 5-3a and 5-6) information needed to satisfactorily judge the solar cell's performance can be obtained. Useful information depicted in the curve shown in Figure 5-3a is the short-circuit current, I_{sc}, open-circuit voltage, V_{oc}, and the maximum power point, P_{mp}. With this information, the solar cell's efficiency, η, fill factor, FF, optimum load resistance, R_{Lopt}, maximum power point current, I_{mp}, and maximum power point voltage, V_{mp}, can either calculated or

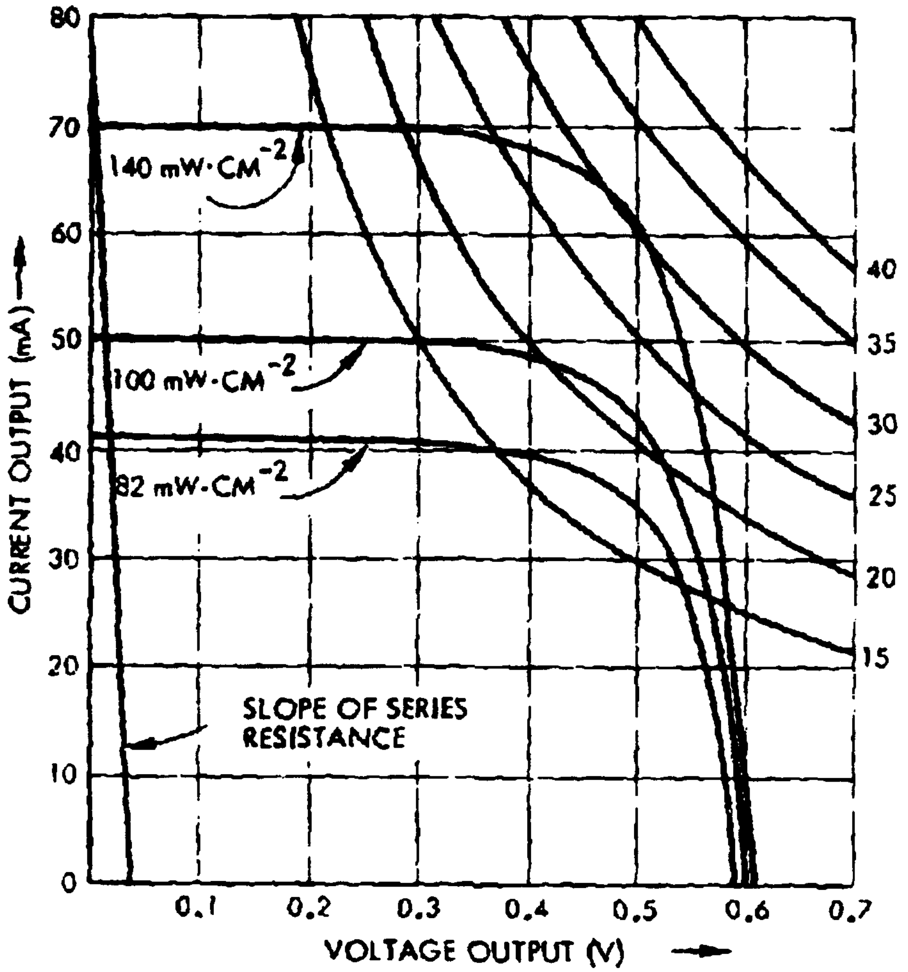

Figure 5-5. I-V Curve Of A Solar Cell At Three Different Illumination Levels [Ref.17:p.3-5.1]

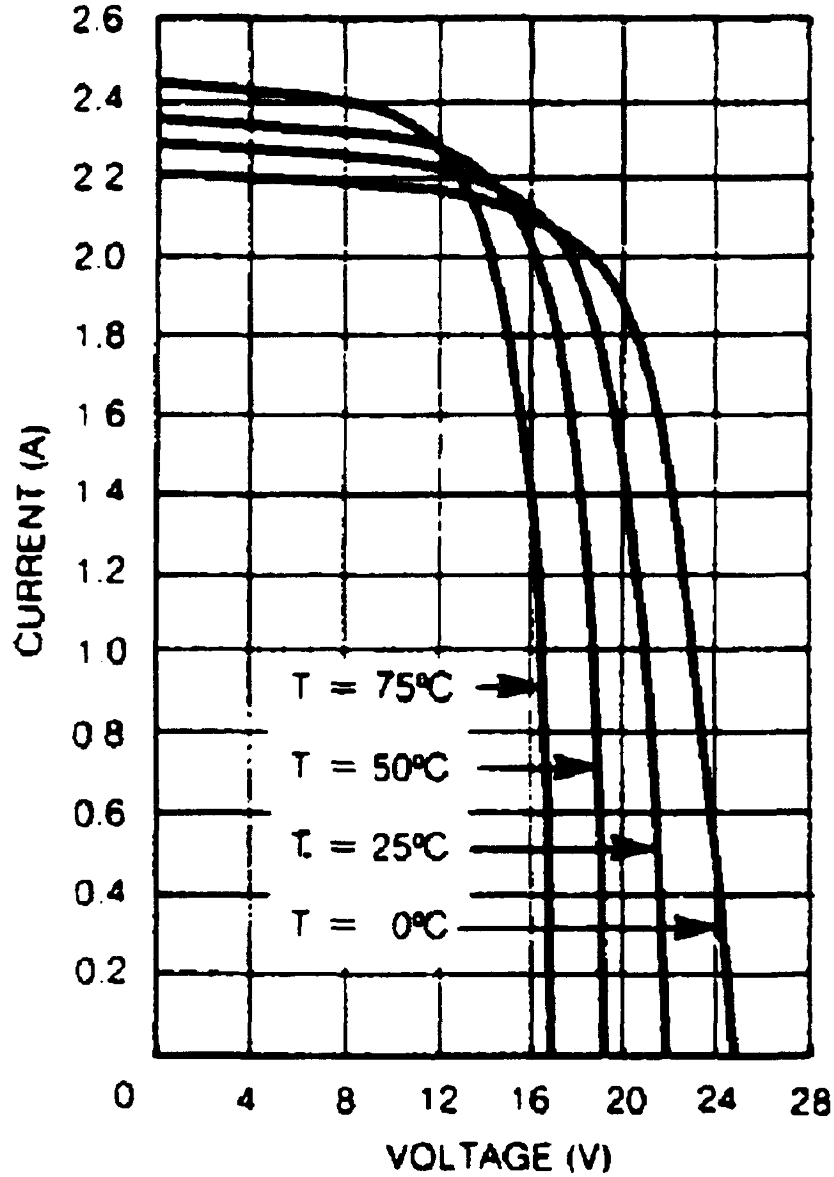

Figure 5-6. I-V Curves At Different Operating Temperatures [Ref.26:p.134]

read directly from the curve.

The maximum power point, P_{mp}, corresponds to the maximum conversion efficiency, η_{max}, of the solar cell. This is represented by the shaded area in the figure. This signifies the largest area rectangle that can be placed within the curve. By drawing a straight line from the origin to P_{mp}, the optimum load resistance, R_{Lopt}, is obtained.

Solar cells are essentially large p-n diodes, and, as such, possess performance characteristics that are most readily expressed in three parameters. These three parameters are short-circuit current, I_{sc}, open-circuit voltage, V_{oc}, and fill factor, FF. In the ideal case, I_{sc} would equal I_L, the light-generated current. V_{oc} may be defined by:

$$V_{oc}=\frac{kT}{q}\ln\left(\frac{I_L}{I_o}+1\right) \tag{5-4}$$

where

k= Boltzmann's Constant

(1.38 x 10^{-23} joules/°Kelvin),

q= the magnitude of an electronic charge

(1.602 x 10^{-19} coulombs),

T= temperature in °Kelvin, and

I_O=the saturation current. [Ref.19:p.79]

The dependence of V_{oc} on I_O makes this voltage parameter also dependent upon the properties of the semiconductor from which the cell is manufactured. The saturation current, I_O, may vary with time for a given material due to exposure to heat, age, radiation, etc. Likewise, I_L may vary with light intensity. Fluctuation of these parameters produces varying voltage values which lie along a characteristic I-V curve. As current through the diode, or cell, decreases from I_{sc}, the voltage begins to increase, rapidly at first, until I_L approaches I_O. As this occurs, voltage across the p-n junction rapidly stabilizes at V_{oc}, as may be seen in Figure 5-7. This effect produces the characteristic knee on an I-V curve. The operating point which maximizes the output power of the cell (where V_{mp} and I_{mp} are the voltage and current, respectively, at the maximum power point) is found on this knee.

b. Fill Factor

The fill factor, FF, is a term that describes the "squareness" of the I-V curve and is a measure of the utilization of the power producing capability of the solar cell. The squarer the curve, the higher the maximum power output and the higher the conversion efficiency of the cell may be for a given I_{sc} and V_{oc}. The fill factor is defined by the following equation:

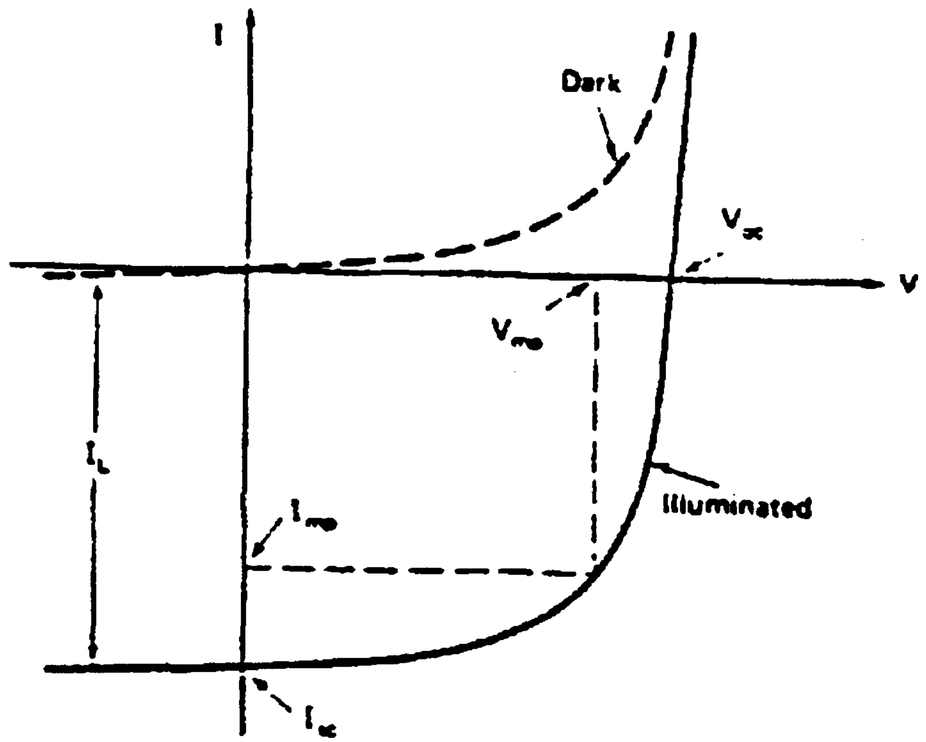

Figure 5-7. Typical P-N Junction Diode I-V Curve [Ref.19:p.79]

$$FF=\frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}=\frac{P_{max}}{V_{oc}I_{sc}} \tag{5-5}$$

where variables are as described previously in Section 4a of this chapter. It should be noted that since V_{mp} and I_{mp} are always less than or equal to V_{oc} and I_{sc}, the fill factor is always less than or equal to one. [Ref.19:p.80]

As shown in the characteristic I-V curve of Figure 5-8, two rectangles are depicted. The smaller rectangle is defined by I_{mp} and V_{mp}, while the larger is identified by the terms I_{sc} and V_{oc}. The ratio of the smaller to the larger rectangle is called the fill factor.

The fill factor is used to compare different solar cells under the same operating conditions. However, it can be misleading when it is used to determine changes in the cell's I-V curve shape due to environmental degradation. It can be shown that when the solar cell operating temperature or illumination intensity is varied over a range in which the I-V curve shape does not change, the calculated value of the fill factor will change. [Ref.21:p.171]

C. PHOTOVOLTAIC MODULES AND ARRAYS

1. Photovoltaic Modules

Individual solar cells produce relatively small amounts of power and therefore must be interconnected into modules to produce enough electricity for most applications.

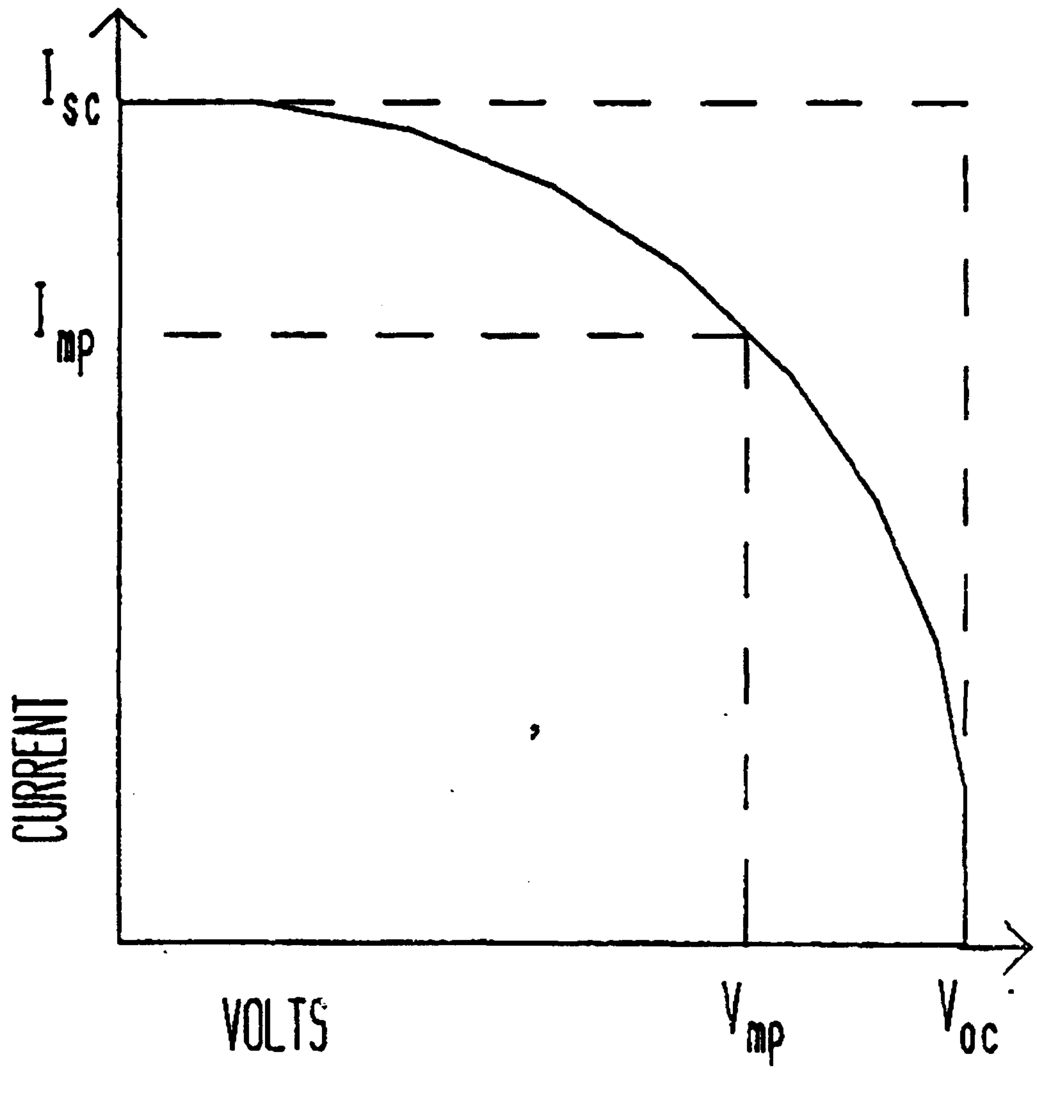

Figure 5-8. I-V Curve Illustrating Fill Factor Relationship [Ref.33]

Cells composing the module can be connected in series to increase voltage, in parallel to boost current, or both to elevate power output. Photovoltaic modules, generally comprising from 15 to 30 cells, are the basic building blocks of PV systems. [Ref.21]

2. Photovoltaic Panels and Arrays

The power available from a single module is usually not enough for a typical application. Consequently, modules are connected together in a manner alike to the individual solar cells of the module. When multiple modules are connected together, care must be taken so that individual modules may be disconnected for repair/replacement without affecting the entire system. Figure 5-9 illustrates acceptable and unacceptable hookup techniques. [Ref.34:pp.15-16]

Photovoltaic panels contain one or more modules. Groups of PV panels are termed arrays. As previously indicated, modules are connected in a series-parallel arrangement within the array, an example of which is shown in Figure 5-10.

3. Bypass and Blocking Diodes

a. Bypass Diode

Bypass diodes, also known as shunt diodes, are connected in parallel with modules of an array. A bypass path around a damaged module is necessary to prevent an entire

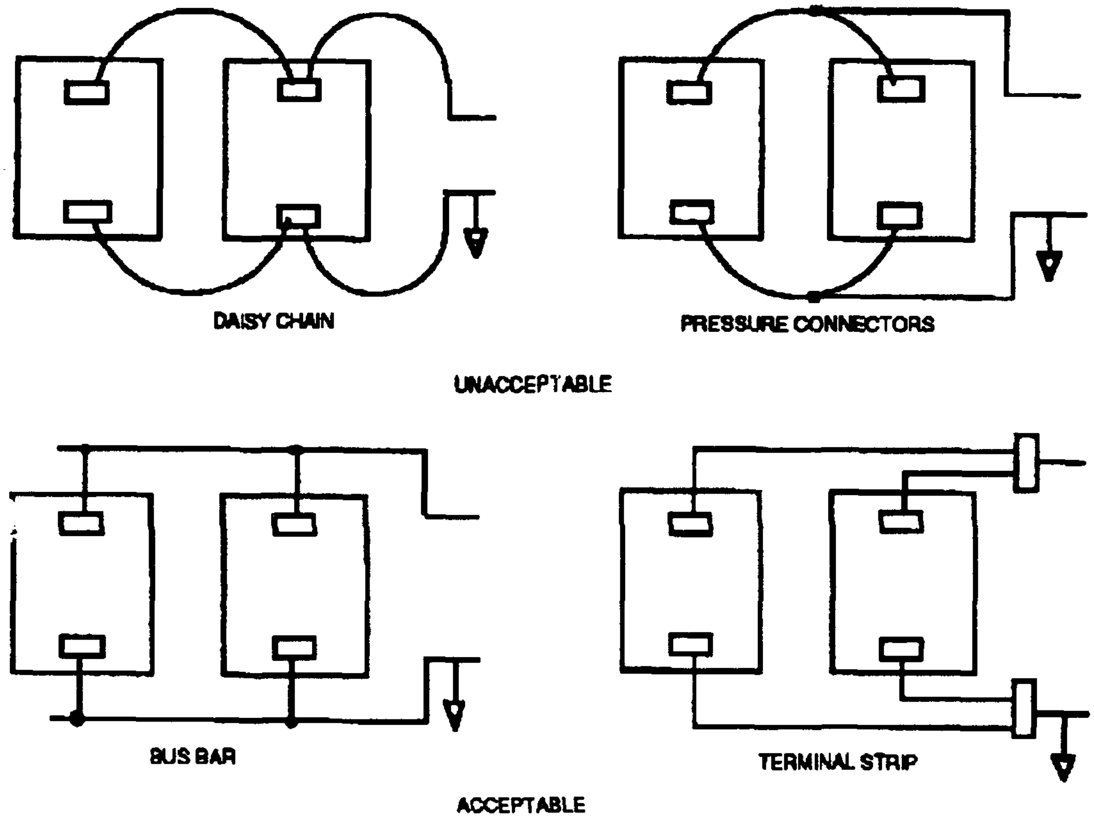

Figure 5-9. Module Connection Methods [Ref.34:p.17]

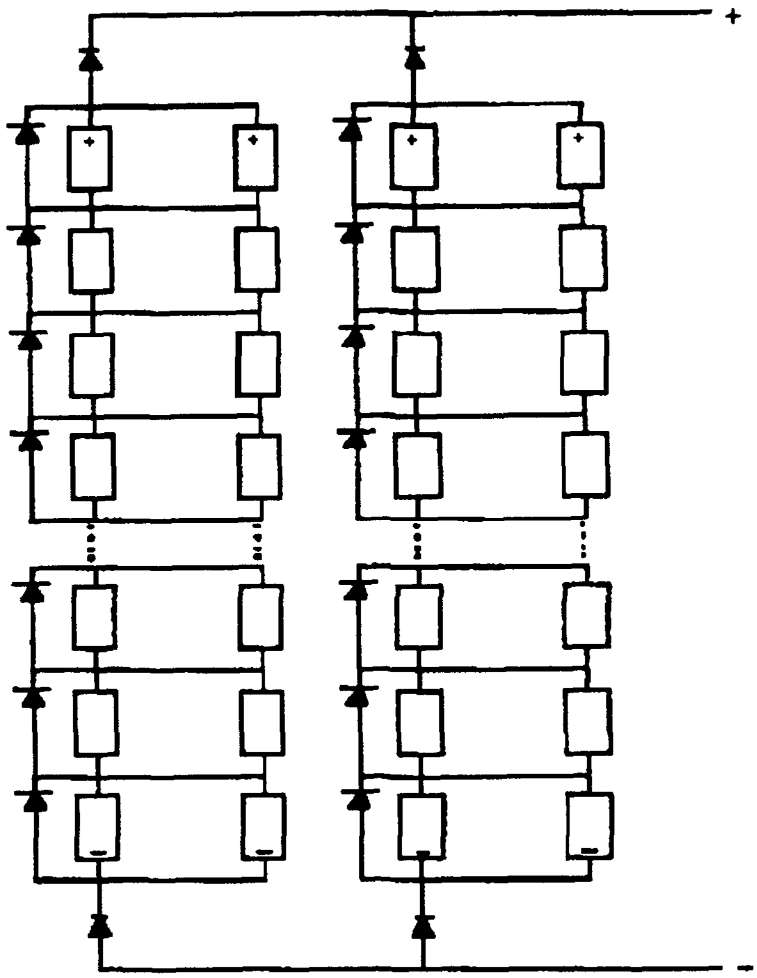

Figure 5-10. Modules in a Parallel-Series Arrangement [Ref.34:p.B-5]

string or system from failing due to the resistance of a failed module that is to large to overcome. When a module in a string fails in an open-circuit mode or becomes shadowed, the bypass diode becomes forward biased, conducts, and routes current around the damaged cell. Hence, power is able to flow from the remaining modules in the string. Figure 5-10 shows a photovoltaic array using bypass diodes to give the required protection. [Ref.17:p.5.5-3 and Ref.34:p.B-5]

b. Blocking Diodes

Blocking or isolation diodes are placed between the power bus and the module string. They conduct current from illuminated strings to the power bus but block current flow from the bus to the string should the string voltage fall below the bus voltage. They prevent the reverse biasing of shaded modules, by allowing current to flow in one direction only. Additionally, blocking diodes check the discharge of the battery into the photovoltaic array during darkness. Figure 5-10 illustrates the use of blocking diodes at the top and bottom of each string. [Ref.17:p.5.5-1 and Ref.34:p.B-4]

4. Photovoltaic Array Classification

Arrays can be permanently installed at a specific angle facing the sun (fixed arrays) or they may continually track the sun and be oriented perpendicular to the sun's rays through the use of a mechanical device (tracking arrays).

[Ref.21] Photovoltaic arrays are also classified as to whether they are flat-plate or concentrating arrays.

a. Flat-Plate Arrays

The most common array design uses flat-plate panels. Whether fixed in place or movable, flat-plate arrays can respond to direct as well as diffuse sunlight. The simplest type of PV array consists of flat-plate PV panels set in a fixed position. The advantages of fixed arrays are their lack of moving parts, little supplementary equipment and relatively light weight. However, less energy per unit area will be produced as compared to a similar tracking array as the angle of orientation to the sun is at best a compromise for year-round operation. The drawback of lower energy output must be balanced against the higher costs (both in dollars and in equipment and maintenance) of a tracking array. To increase efficiency, flat-plate arrays can be equipped with reflector mirrors, which may increase the light-gain by as much as one-third.

Except for sites near the equator, a flat-plate array should not be in a horizontal position. For a northern hemisphere location, the array should be tilted southward towards the equator. Positioning of the array in this manner can increase the energy collection. If the array is to be permanently fixed, the optimum tilt of the array should be calculated as follows

$$\theta=\phi+15^{\circ} \tag{5-8}$$

where θ is the array tilt angle, and ϕ is the latitude of the array. [Ref.7:p.96 and Ref.8:p.678] The positioning of the fixed-array at the calculated angle will result in the optimum annual energy collected (winter and summer).

An improvement in the energy collected can be obtained if the tilt of an array is changed in accordance with insolation data, if available. For example, if data is available as shown in Appendix C, the array's tilt should be changed to the optimum angle for energy collection each month. However, the angle is normally changed semiannually, though it should be understood that semiannual angle adjustments will not result in large energy collection gains. Figure 5-11 depicts semiannual changes to a flat plate array. [Ref.35:p.27]

Photovoltaic arrays that track the sun across the horizon, as shown in Figure 5-12, offer the best energy collection of the flat-plate arrays. However, the cost and mechanical complexity are significant drawbacks. Tracking arrays are not normally utilized.

Additional information on flat-plate arrays can be found in the *Solar Array Design Handbook*. [Ref.21]

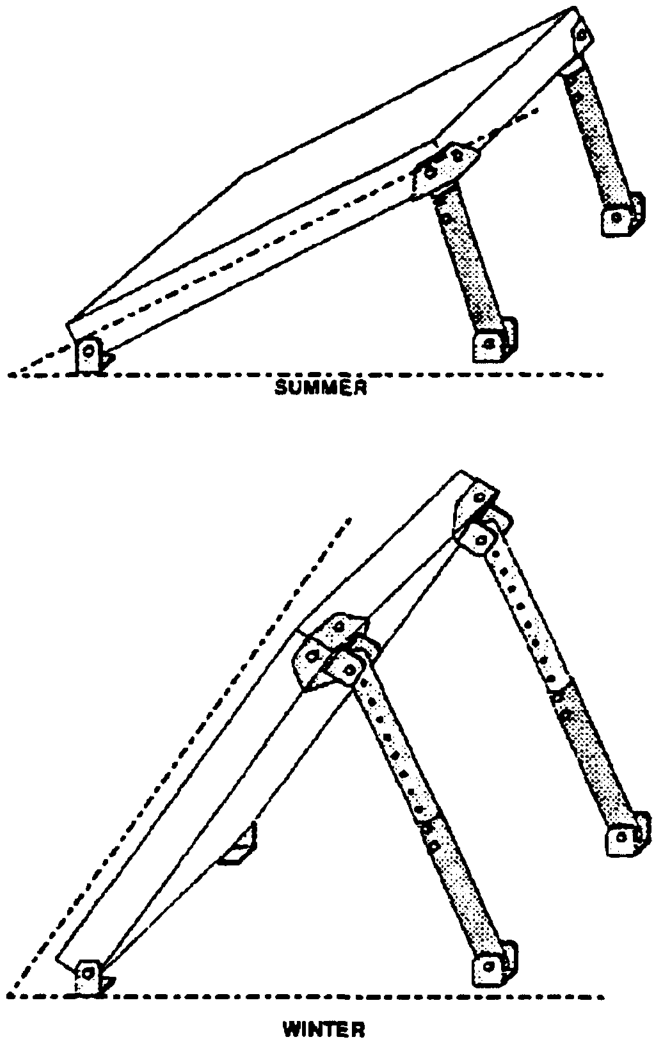

Figure 5-11. Adjustable Flat-Plate Tilted for Summer and Winter Solar Angles [Ref.35:p.27]

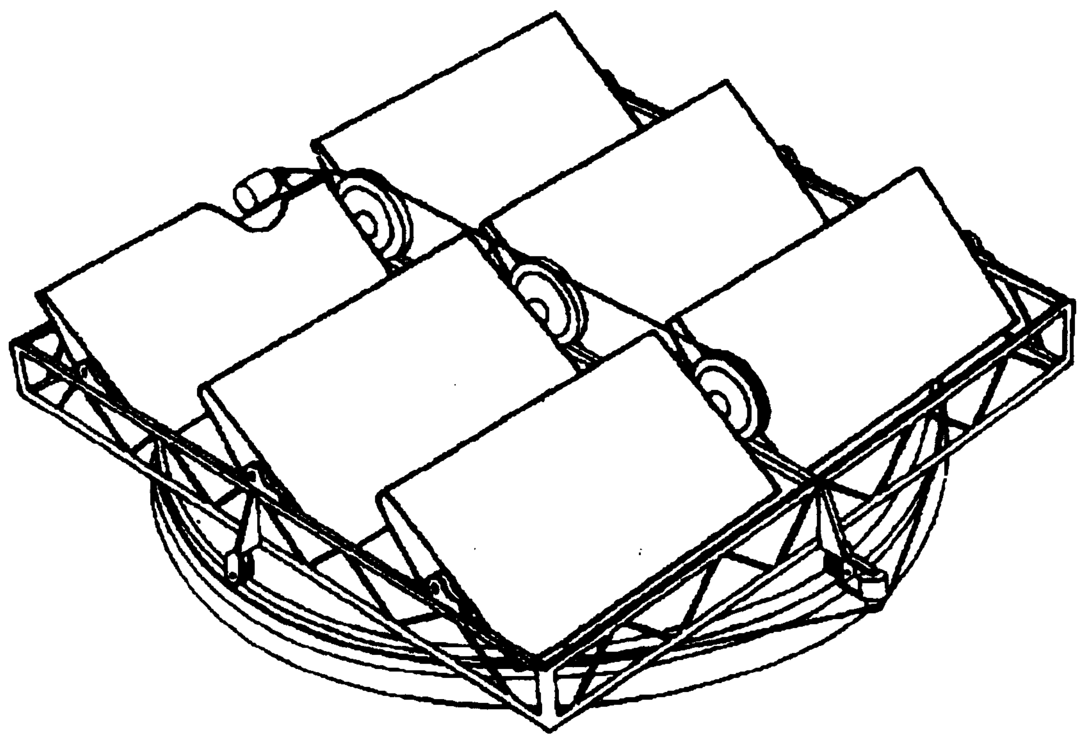

Figure 5-12. Typical Tracking Array [Ref.36:p.132]

b. Concentrating Array Systems

A way to reduce photovoltaic power costs is to reduce the area of solar cells required for a given power output by concentrating the sunlight. This is accomplished through the use of a concentrating array. In this way, system costs can be displaced from the cells to the concentrating elements and the tracking system, if so designed. Generally, the higher the concentration ratio, the smaller range of angles of incidence the system will accept and the higher the tracking capability the system must have [Ref.37:pp.702-704]

When using concentrating arrays, cell temperature will increase, thereby lowering its efficiency. Therefore, provision must be made to cool the cells. However, assuming constant temperature (providing the cooling process can maintain cell temperature), as concentration ratio increases, so does overall cell efficiency. [Ref.37:pp.707-712] Reflective mirrors and optical lenses may also be used in conjunction with concentrating arrays. However, they will not be discussed in this thesis.

D. ADVANTAGES/DISADVANTAGES OF SOLAR ENERGY AND PHOTOVOLTAIC SYSTEMS

1. Advantages

Some of the more pertinent advantages of solar energy, as an alternative, are listed and briefly described below:

a. Continuously Renewable Source

Due to its origin from the sun, solar radiation (insolation) is virtually inexhaustible and has almost unlimited availability. Because of the universal nature of solar energy - available to all peoples of all countries without regard to physical, political or human boundaries - its generation is not centralized or limited to specific locations.

b. Relatively Low Cost

While a cost analysis was not included as part of this thesis, it should be noted that solar energy is free, except for the initial capital cost of capture and conversion to a usable form. Once a solar energy system is installed power costs remain steady. The sun's energy from that point on is "free" and has virtually no costs except those associated with maintenance and repair.

c. Cost-Effective Source

Fossil fuels are extremely costly now and will continue to escalate in price as supplies diminish. This means solar energy systems are cost-effective (with respect to fossil fuel systems) now and should continue to improve in the years ahead. Solar energy equipment installed today has a life expectancy of between 20 and 25 years. An additional advantage often overlooked is that maintenance costs are very

small compared to those of most fossil fuel generating systems. [Ref.38]

d. Environmentally Attractive

Solar energy is quiet, clean, and non-polluting (disregarding production of the solar cells). In addition, solar energy requires neither transmission of fuel, large central distribution or generating plants, nor distribution lines, etc. It can be produced in small electrical converters -solar cells or collectors-wherever the energy is to be used.

2. Disadvantage

The major drawback in the use of a photovoltaic system as a power source is the initial cost of the system. However, it is cost-effective for some remote applications, where the cost of extending utility lines or operating diesel generators is prohibitive. Nonetheless, photovoltaic power is not yet cost-competitive with utility-grid power, which comprises the bulk of the power market in the United States. An additional problem confronting the initial cost of the system is the necessity of providing a storage system. The storage system must be drawn upon to provide power when the photovoltaic array is inoperable due to darkness or cloud cover.

A secondary disadvantage is the necessity of having accurate insolation data prior to the system design. Since the availability of solar radiation varies by both location and time, a prior knowledge of the history of the insolation

at a site is crucial to appropriate selection of the array system.

E. COAST GUARD APPLICATION

1. Power Requirements

Based upon the power specifications as documented in Chapter II, the average power requirements, including 30 percent system losses, for the main communications sites and the microwave relay sites are as follows: 10.97 kWh/day and 0.823 kWh/day for the main communications and the microwave relay systems respectively.

2. Photovoltaic Only System

The most popular commercially available array panel has the following specifications:

- Each panel produces approximately 50 watts from an irradiance of roughly 1 kW/m^2 (the efficiency is approximately eleven percent).
- A single panel is approximately one meter (m) in length and 0.5 meters in width, for a total area of approximately 0.5 square meters (m^2).
- Each panel weighs approximately 5.9 kilograms (kg).

For additional information on the specifications, refer to reference 39.

a. Average Daily Solar Insolation

Using insolation data from Appendix C and site data from Appendix A, and for illustration purposes only, the two extreme site locations (55° and 60° N. latitude) can be

evaluated for the potential of using a solar array only power system. The array tilt was assumed to be adjusted semiannually (June and December) as shown in Figure 5-11. The average daily total insolation estimate for a 55° N. latitude is 1.4 kWh/m^2 at a tilt of 80° in December, while 4.7 kWh/m^2 are available at a 20° tilt in June. For a 60° N. latitude site, 0.79 kWh/m^2 at an 80° tilt and 4.9 kWh/m^2 at a 20° tilt are available in December and June respectively. The two sample sites represent the range of latitudes for the remote communications stations.

The average insolation striking a solar panel is obtained by multiplying the average daily total insolation estimate by 0.5 m^2. For the 55° site, each solar panel receives approximately 0.7 kWh/day in December and 2.4 kWh/day in June. The 60° site receives an average of 0.4 kWh/day and 2.5 kWh/day in December and June respectively.

b. Average Daily Output Power Per Panel

To determine the average daily output power per panel, the average daily solar insolation per panel is multiplied by 0.10 (ten percent efficiency). For a 55° site, 70 watts per day (W/day) are produced in December while 235 W/day are produced in June. For the 60° site, 40 W/day and 245 W/day are produced in December and June respectively.

c. *Number Of Solar Panels Required*

The number of solar panels required to support the main communications system requirement of 10.97 kWh/day and 0.823 kWh/day for the microwave repeater system, is based on the power outputs as calculated in the preceding section. For the 55° site, a minimum of 157 panels would be necessary to provide 10.97 kWh/day in the month of December to operate a main communications site utilizing a solar only system. In the month of June, 47 panels would be required. To operate a microwave relay site, 12 panels and 4 panels would be required in December and June respectively.

For a 60° site, 275 and 45 panels would be required for a main communications site in December and June respectively, while 20 panels and 4 panels would be required for the same months for a microwave station.

Although accumulations of dirt and dust on the array will have some effects on the power production, studies have shown that the effects are minor as long as routine cleaning of the panels occurs. With respect to the specific Coast Guard application, semiannual cleaning will be accomplished. [Ref.18:p.24-5]

3. Decision

From the above results, and considering the surface area of typical 50W solar panels (roughly 0.5 x 1 meter), one can determine that the area required to produce solar power

can range from a high of 138 m^2 for 60° sites in December to a low of 22.5 m^2 for 60° sites in June with 45 panels. Though the size of the array precludes winter usage, the array size is feasible for use in the summer months.

This information leads to the conclusion that a solar only system is not feasible nor economical for use year-round, due to the physical size of the array. However, it could be an attractive solution as a part of a hybrid power system, where the photovoltaic array is utilized during the summer months, and where an alternative can produce the majority of the power needed for winter months.

4. Possible Improvements

Possible improvements to the system could include the use of a concentrating array, a tracking array, or gallium arsenide solar cells. However, for this specific Coast Guard application, these possibilities are not cost-effective.

VI. WIND-POWERED GENERATOR SYSTEM

This chapter provides an overview of wind energy, wind resources and wind turbine engineering design. However, all aspects are not covered in great detail as the wind engineering field is extensive. There are a multitude of available reports, manuals and texts that address the mechanical and electrical design aspects, location of the site, resources, etc. An excellent reference for the overview of engineering design of wind turbines including aerodynamics, structural analysis and systems engineering, rotor design, etc., is Eggleston and Stoddard [Ref.40].

A. FUNDAMENTAL ASPECTS OF WIND ENERGY

Systems drawing power from the wind have played an important role in providing energy to mankind over the past 2000 years, or more. The wind has been used as a source of power for ships for many centuries. Throughout history many countries have owed their prosperity and even their existence to the wind and sailing ships.

1. Historical Perspective

The earliest use of wind turbines were simple vertical-axis machines used for grinding grain. They were first recorded in Persia as early as about 200 B.C. However, the exact date is uncertain. It was a carousel-like device

that rotated around a common pole. The wind was captured by collections of reeds. The type of machine is one of the simplest designs for capturing energy from the wind. It revolves without respect for the direction of the breeze. [Ref.41:pp.2-4]

Horizontal-axis windmills were in extensive use in the Middle East by the 11th century. The windmill dates to 1101 A.D., and 1105 A.D., in England and France respectively. Conventional mills were used to grind corn and pump water. They were most likely introduced to Europe by returning crusaders. In the late 12th and early 13th centuries, windmill use spread to the Netherlands, Germany, Denmark, and many other countries of the world. [Ref.14:p.577 and Ref.42:p.32]

By the 14th century, the Dutch were the leaders in windmill design. Windmills were extensively used for draining the marshes and lakes of the Rhine River delta.

In the 16th century, the world saw rapid improvements in the harnessing of the power of the windmill. The first oil mill was built in Holland in 1582. The invention of the printing press led to the design and construction of the first paper mill in 1586 [Ref.43:pp.5-6]. The first wind-driven sawmill was developed in the late 16th century [Ref.41:p.18].

One of the most significant advances in the windmill industry occurred in the 18th century. Edmund Lee, an English blacksmith, ascertained that through the use of a simple

device, the rotor of a windmill could track the changes in wind direction and remain facing into the wind. This simple invention was a secondary rotor attached to the windmill tower at a 90° angle to the main rotor (refer to Figure 6-1). Lee observed that when the primary rotor squarely faced the wind, the secondary rotor or fantail twirled slowly. When the wind changed direction, the fantail whirled faster and pulled the main rotor into the wind. This was one of the first mechanical feedback control devices. [Ref.41:pp.19-21]

The wind turbines of today are based upon Lee's invention. While small turbines use a weathervane tail or fantail, most large machines are mechanically pointed. A small vane on or near the turbine tracks the motion of the wind. A moving optimum position average is determined based upon signals sent to a computer. When the average differs significantly from the actual position, the propellers are turned into the wind [Ref.40:pp.48-51].

Windmills came to the Americas in the late 1700s or early 1800s. The English, Spanish, Germans, Swedes, Portuguese and Dutch established systems in various settlements. During the mid-1800s, windmills moved west with the pioneers, where the familiar multi-vane farm windmill was developed [Ref.42:pp.29-39].

Windmill use was at its peak in the 19th century. In the Netherlands, some 9,000 windmills were being used for a wide variety of purposes, including land reclamation

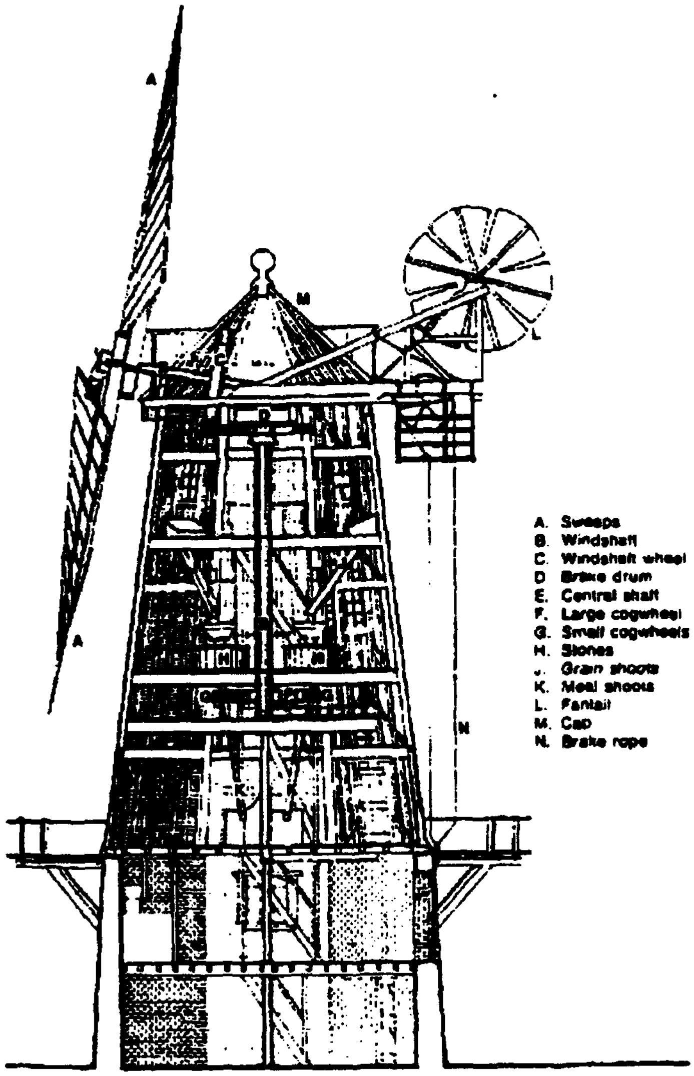

Figure 6-1. Nineteenth Century Windmill [Ref.44:p.5]

[Ref.43:pp.5-6]. More than 10,000 windmills were in operation in the lowlands of the British Isles [Ref.41:pp.18-19]. By 1889, there were more than 70 manufacturers of windmills in the United States. The windmill industry flourished in this country and was a major part of the export market until the start of the 20th century [Ref.41:pp.21-25].

The development of the steam engine, marked the beginning of the windpower industry's rapid decline. By 1919, less than 2,000 windmills were in operation in the Netherlands [Ref.43:p.6], and the American industry had been reduced to less than 30 factories [Ref.41:pp.25-28].

Even though the windpower industry was in decline, windmills were widely used for generating electricity into the early 1930s, especially in rural areas. However, the establishment of the Rural Electrification Administration (REA) in 1935, brought that to an end. The purpose of the REA was to bring cheap centralized electric power to the nation's farms and ranches via electrical cooperatives. Power lines spanned the country, public and private utilities flourished, and windmills fell into disuse and disrepair. [Ref.41:p.28 and Ref.45:p.7]

Though the death knell was sounding for the windmill industry, the belief that energy could be captured from the wind did not go away. The goal was to design technically feasible and economically viable windmills for large-scale power generation. [Ref.14:p.578]

In the early 1940s, the largest, in size and capacity, wind turbine was constructed. The Smith-Putnam turbine, developed by Palmer Putnam and the S. Morgan Smith Company, generated 1.25 megawatts of power when wind speeds reached 30 miles per hour. It demonstrated that large-scale turbines were technically feasible for the harnessing of wind power. The turbine was somewhat successfully operated through 1945, though the project was abandoned due to the scarcity of materials caused by U.S. war efforts and the excessive costs. [Ref.44:pp.7-8 and Ref.45:pp.6-8]

The government started an intensive search for alternate sources of energy in response to the energy crisis of the 1970s. The Department of Energy (DOE) was established to lead and provide a base of information related to the search. The DOE oversaw a research and development program that saw wind-power technology machines developed from the kilowatt to the megawatt range. Additionally, a multitude of companies in the private sector sprang up and pushed forward with innovative wind technology ideas. [Ref.45:pp.8-9]

2. Historical and Current Uses

In addition to the use of wind for sailing ships, other early traditional uses of wind power were found in agricultural and industrial applications such as grinding grain and pumping water for watering livestock and irrigation of fields. Small wind turbines were also used for charging

batteries that provided current for electric lighting. [Ref.14:p.577 and Ref.41:p.4]

Since the mid-19th century, over 6 million small windmills have been constructed in the United States to generate electricity and pump water among other operations. It is estimated that over 100,000 may still be in operation today. A large number of these windmills in use today are for watering livestock on ranges in remote areas. [Ref.42:pp.29-39 and Ref.43:p.7] Additionally, there has been an increasing use of small wind turbines to provide minimal electricity and lighting to isolated cabins which cannot economically be connected to the public supply grid [Ref.46:pp.1-2].

The idea of generating electricity with wind power is not new. However, the kind of attention that it is getting today in terms of time and money for research and development is encouraging to planners looking for renewable energy sources to satisfy ever-growing national demands for energy.

3. Wind Resources

a. General

The wind is one of the largest derivatives of the energy of the sun. It is behind the use of photovoltaic collectors used to capture the sun's energy and energy contained in the oceans. Because dams and land flooding are not involved, wind use is environmentally more benign than water power. Although wind energy is available no matter what

the wind conditions, the bulk of the power lies in the upper reaches of the atmosphere and is not easily accessible. However, strong surface winds are available in portions of the United States. For example, powerful areas of concentrated wind are available on the Great Plains, portions of the East and West coasts and in Alaska's Aleutian Chain. [Ref.13:pp.630-636] Appendix D documents monthly and average annual wind speeds for various locations in Alaska.

b. Source Overview

Winds are caused by the asymmetric solar heating of the earth. In daytime, oceans and lakes absorb the sun's energy. Additionally, much of the sun's energy is consumed in the process of water evaporation. Consequently, the air over bodies of water remains relatively cool. On the other hand, the land absorbs less sunlight than the water, while a large portion is reflected back into the atmosphere. This results in a heating up of the air over land. The cooler and denser air over the water moves in over the land as the heated air expands, becomes lighter, and rises. Hence, the local shoreline breezes are created from the displacement of the warmer air by the cooler air. [Ref.43:pp.1-3]

At night the flow of this wind is reversed, since the land cools at a much faster rate than the water. The warm air rising from the water is supplanted by the cool air sweeping in from the land. [Ref.43:pp.2-3]

Similar breezes develop in the mountains and valleys. In daytime, air rises along the warm slopes heated by the sun. At night, the cool air gravitates towards the valleys. Figure 6-2 illustrates the development of these breezes. [Ref.41:pp.1-2]

Similarly, though on a substantially larger scale, the generation of circulating planetary streams are caused by the more concentrated heating of the earth near the equator relative to the heating at the poles. Cold polar winds move towards the equator, while the tropical winds rise and move towards the poles. [Ref.41:p.1 and Ref.43:pp.2-3]

The rotation of the earth about its own axis and about the sun has a major effect upon the planetary winds. The inertia in the warm air tends to twist it to the east as it moves toward the poles. Conversely, because of its own inertia, the cooler air from the poles generally curls to the west. This results in a counterclockwise flow of air streams in the northern hemisphere while there is clockwise circulation in the southern hemisphere. Seasonal changes in wind direction and strength are caused by variations in the heat received from the sun. These variations result from the earth's axis being inclined at an angle of 23.5° with respect to its axis of rotation about the sun. Figure 6-3 illustrates how the earth's rotation affects winds. [Ref.41:pp.1-3 and Ref.43:pp.1-3]

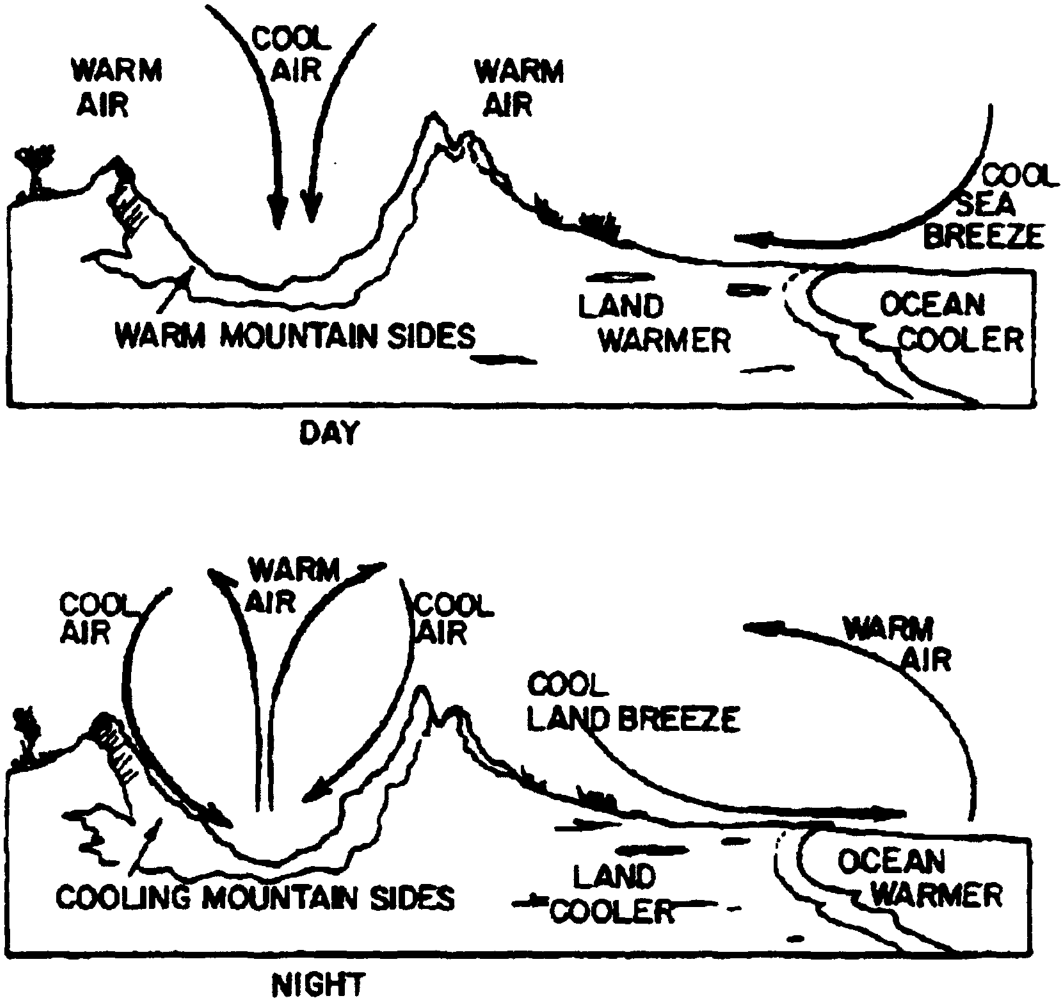

Figure 6-2. The Generation of Land and Ocean Winds [Ref.41:p.2]

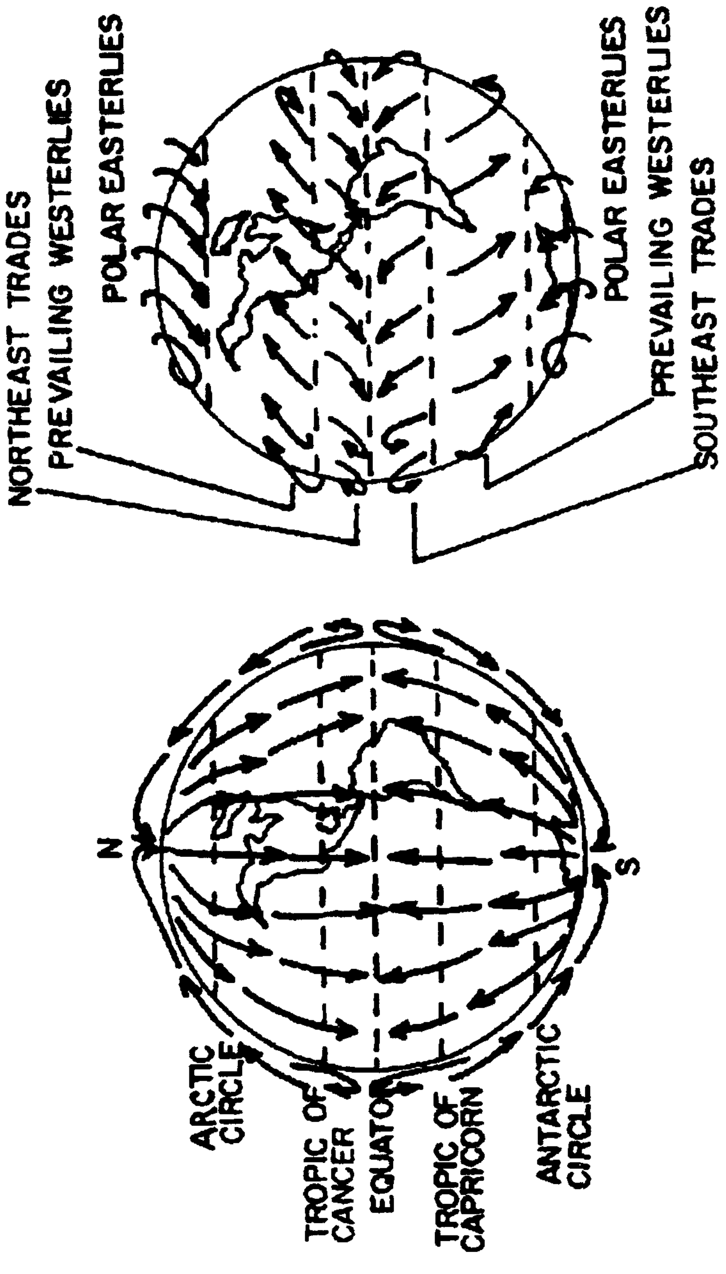

Figure 6-3. Direction of Winds
A. Non-rotating Earth
B. Rotating Earth [Ref.41:p.3]

4. Characteristics

When considering the use of wind for power purposes some important questions need to be asked. Is there sufficient wind to be economically useful? What amount of wind energy can be expected? How is the wind distributed? What are the probable durations and effects of very high wind speeds or of calm periods during any given period? These questions are discussed below.

a. Site Selection

Site selection is discussed in general terms as the remote communications sites in Alaska have previously been determined by the Coast Guard.

Inevitably, power developed by the wind is thought of as free. While the source is undeniably free, because of its low density, air must be drawn upon in large quantities to provide significant energy output. Without optimum positioning of the turbine site, and close attention paid to its design and construction, the plant required to capture the wind and extract the energy may be expensive and uneconomical. The lure of free electricity is large, even though the electricity isn't free. The lure of bringing power to remote sites where power was previously unavailable or difficult to provide and maintain is even larger. [Ref.14:p.13 and Ref.46:p.2]

It is almost unnecessary to say that a favorable site for a wind driven plant must have a high average wind speed. The fact that the power in wind is proportional to the cube of its speed makes wind speed a prime consideration in the location of the wind turbine site. The annual wind speed average and distribution, or frequency of occurrence, is clearly of great importance in assessing the energy potential of a site. However, wind speed and distribution depend upon certain attributes. Among the features of a site that lead to high wind speeds are:

- Its geographic position.
- Its detailed location, including altitude and distance from the sea.
- Its exposure, including distances to higher ground and other obstacles in the immediate area likely to screen the system, especially in the direction of the prevailing winds. [Ref.43:p.29 and Ref.47:pp.13-19]

(1) Geographic Location. For proper site evaluation, it is imperative to know the distribution of the wind. A wind atlas for the United States detailing the wind distribution was prepared by J.W. Reed at Sandia Laboratories [Ref.48], using the data available from National Climatic Center records. The atlas documents the annual average of the available wind power. Additionally, the atlas reveals that areas of high wind power generally have their highest winds

during the winter season, with much less available power in the summer and fall seasons. [Ref.14:p.597]

Today, wind energy systems are well-developed and construction of new installations does not require the development of new technology. However, since the energy content of the wind is proportional to the cube of the wind speed, wind power systems are economical only in regions where winds of sufficient strength and regularity occur. Cost approximations of wind energy systems tend to be consistent with other energy sources as long as a favorable wind regime is anticipated. Additionally, wind energy plants have to be large to produce significant power. [Ref.14:p.13]

(2) Height Above Ground. The wind turbine's height above ground joins its geographic location in influencing wind power density. Wind speed increases with height in a rather complex way. To obtain a rough estimate of the wind speed at a certain height, it is assumed that wind speed is proportional to the one-seventh power of the height above ground.

The wind speed, V, slowly increases with height above ground, giving a limited inducement for making windmills high. The equation relating wind speed and height above ground is as follows:

where

V= the wind velocity in m/sec,

$$V = vZ^{1/7} \qquad (6\text{-}1)$$

v= the wind speed at ground level in m/sec, and

Z= the height above ground in m. [Ref.44:pp.243-244]

The exponent of 1/7 used in Equation 6-1 is actually an average over the useful range. In reality, the vertical variation of wind speed is different for a gentle wind and a strong wind. The exponent varies from roughly 1/6 in a 15 mile per hour surface wind to approximately 1/8 in a 33 mile per hour wind. For surface winds above 50 miles per hour, the exponent drops to zero. Wind speed, V, is relatively independent of Z or about the same at all heights for very strong winds. [Ref.44:p.243]

b. Power Available in the Wind

Wind is air in motion, and the air has mass. When this mass has velocity, the resulting wind has kinetic energy which is proportional to ½[mass x $(\text{velocity})^2$]. The mass of air passing in unit time is ρAV, where ρ = the density of the air in kg/m^3, A = the area of the blade circle in m^2, and V = the wind velocity in m/sec. Hence, the kinetic energy passing through the area in unit time is

$$P = \frac{1}{2}\rho AV \cdot V^2 = \frac{1}{2}\rho Av^3 \qquad (6\text{-}2)$$

This is the total wind power that is available for extraction by a wind-driven machine, yet only a fraction can actually be extracted. However, it should be noted that small increases in wind speed result in significant increases in the available wind power. [Ref.46:p.22]

c. Estimation of the Energy Obtainable from the Wind

The function of a wind turbine is to produce mechanical energy from the extracted energy of the wind. The mechanical energy can be converted into other forms of energy. In a real system, energy losses occur because of drag effects and the rotational motion of the wind imparted by the blades. [Ref.14:p.583]

In 1927 Alfred Betz of Göttingen, Germany computed a precise formula for the power that is available from the wind. While conducting studies on wind energy, he applied the simple momentum theory, established by Rankin and Froude for the ship's propeller, to the windmill [Ref.46:pp.191-192]. Betz showed that the maximum fraction of power that can be extracted from the available power was ideally 16/27 or 0.593 [Ref.43:p.31 and Ref.46:p.23].

The theoretical maximum power able to be extracted from the wind by a system of 100 percent efficiency is

$$P_{max} = 0.593 \frac{\rho A V^3}{2} \qquad (6-3)$$

where the variables are as defined for Equation 6-2 [Ref.43:p.31 and Ref.44:p.248]. The factor 0.593 is known as the Betz coefficient. Betz's formula showed the following:

- That the power in the wind is directly proportional to the cube of the wind speed. For example, doubling the wind speed yields an eight-fold increase in the power.
- That the power in the wind is proportional to the area swept by the rotor. For instance, doubling the diameter of the rotor yields a four-fold increase in power output.
- That the power in the wind is proportional to the density of the air. However, changes in air density are commonly neglected since changes in wind speed have a much larger effect on the power.
- A maximum of 59.3 percent of the total power available from the wind can be extracted. However, because of imperfections, mechanical and electrical losses in any machine, the fraction of power that can be extracted is less than the Betz coefficient. [Ref.47:pp.3-6]

d. High Wind/Calm Wind

The duration of high wind and no wind or calm wind periods suggests times when a wind-driven plant will not produce an energy output. In the high wind situation, the system may have to be shut down to avoid damage. The duration of calm spells is important because it indicates periods where the loads must be supported by power drawn from storage. Figure 6-4 shows how the annual percentage of winds under 4 mph increases as the annual mean wind speed falls. This percentage ranges from approximately three percent for mean wind speeds of 24 miles per hour (mph) to 25 percent for annual average wind speeds of below 7 mph [Ref.46:p.51]. The

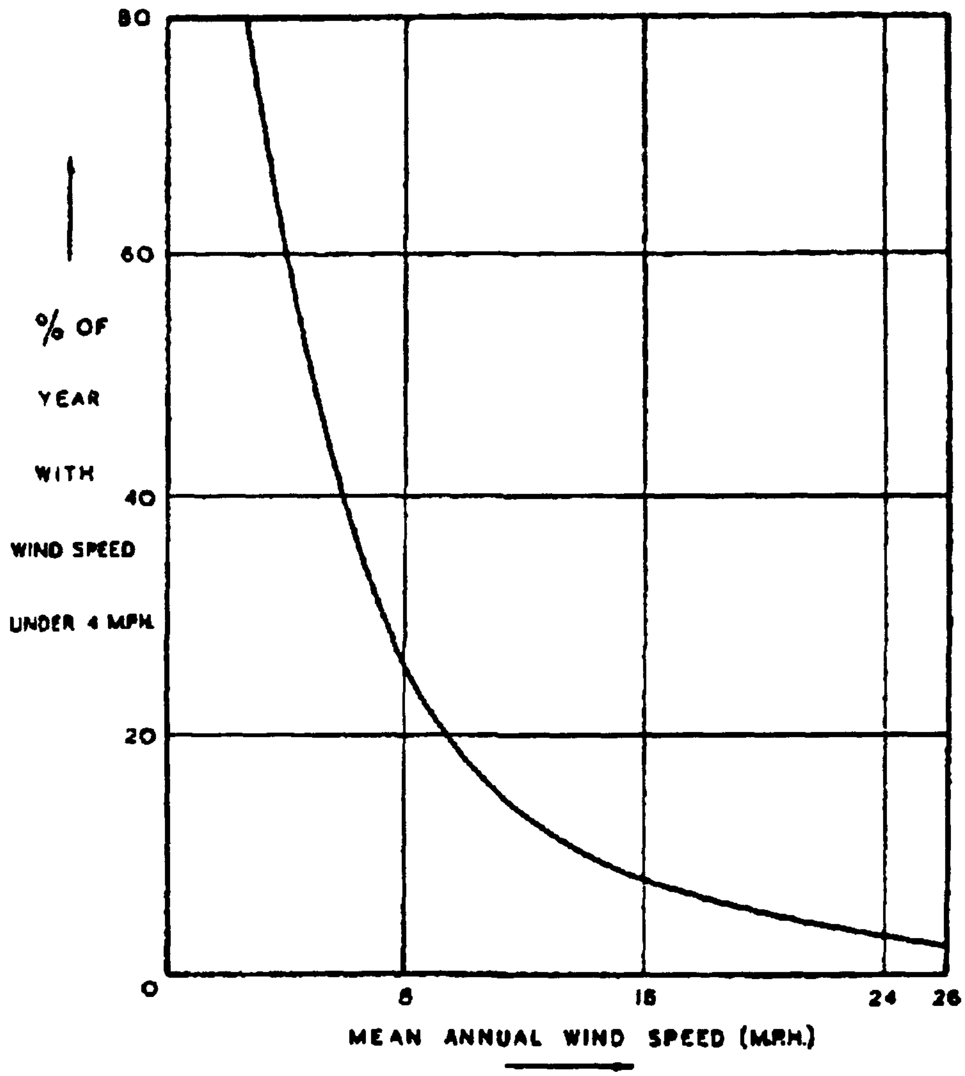

Figure 6-4. Annual Duration of Wind Speeds Under 4 MPH [Ref.46:p.51]

storage requirements may be pushed to the limit if an unplanned number of consecutive days of calm weather occur.

B. SYSTEM SELECTION

The generic term "wind turbine" is defined as "... a machine with rotating blades that converts the kinetic energy of a flow of air (wind) into useful power [Ref.40:p.1]," usually in the form of a rotating shaft. This mechanical motion can be used to operate machinery or to generate electrical power.

1. General

A small wind turbine can produce four types of energy, described as follows:

- Direct heat. It can heat water to useful temperatures.
- Mechanical power. It can operate machinery or pump water.
- Alternating-current electricity. It can provide the power necessary to operate a wide variety of modern electrical devices.
- Direct-current electricity. This is useful in remote applications with battery storage. [Ref.45:p.33]

Small wind turbines can meet continuous power demands of approximately 20 watts, with a mean wind speed of 5-7 m/s. However, higher wind speeds make wind turbines more economically attractive.

2. Types of Wind Turbines

a. Horizontal Axis Wind Turbines (HAWT)

Horizontal axis wind turbines are machines in which the axis of rotation is parallel to the direction of the wind stream, typical of conventional windmills. They usually have two to four thin propeller blades. Wind turbines with a horizontal axis are the most prevalent in the commercial world. An example of a horizontal axis wind turbine is shown in Figure 6-5. [Ref.49:pp.16-18]

b. Vertical Axis Wind Turbines (VAWT)

Vertical axis wind turbines are machines in which the axis of rotation is perpendicular to both the surface of the earth and the direction of the wind stream. Vertical axis wind turbines incorporate many of the same principles as HAWTs. An advantage of VAWTs over HAWTs is that the rotor does not need to be repositioned when the wind direction changes. However, the design is much more specialized and complex. [Ref.49:pp.18-19]

3. Efficiency

The majority of windmills in use today use propellers that are similar to a reverse operating airplane propeller. "In fact, a windmill propeller is exactly equivalent to an airplane propeller advancing through a stationary fluid with the speed of the wind but in an opposite direction [Ref.14:p.581]." That is, the propeller of a windmill

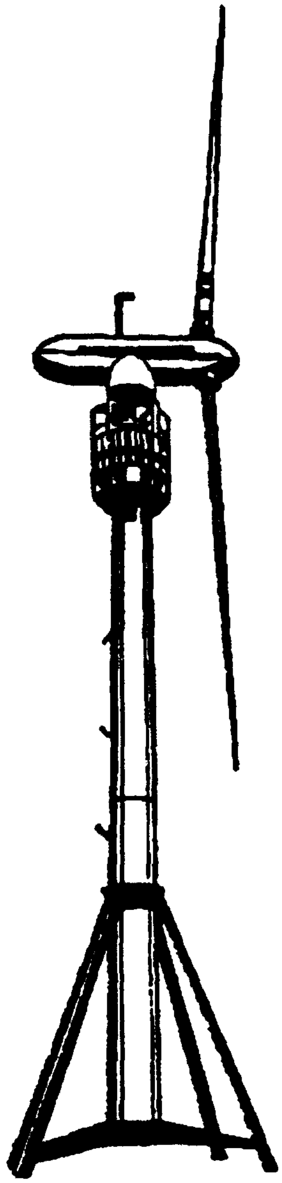

Figure 6-5. Generic Modern Wind Turbine [Ref.49:p.33]

operates with a negative torque and a negative thrust. Unlike an airplane propeller, the thrust of a windmill is not important. It is only used to calculate the loads and stresses in the windmill structure. The efficiency of an ordinary propeller is defined as the ratio of the thrust it develops times the propeller speed to the power input required to drive it. However, the windmill propeller does not move. Therefore, another definition of efficiency was developed specifically for the windmill. The efficiency of a windmill, η_w, is defined as the ratio of the work done per unit time to the kinetic energy per unit time of the fluid (air) passing through the area of the rotor, or

$$\eta_w = \frac{8nT}{\pi \rho V^3 D^2} \tag{6-4}$$

where

V= the wind velocity in m/sec,

D= the propeller diameter in m,

ω= the rotational speed in rad/sec,

ρ= the density of the air in kg/m^3, and

T= the torque in kg·m. [Ref.14:p.582]

4. Rated Wind Speed

One of the most important design features of a wind-driven generator is the rated wind speed. This is the lowest wind speed at which full output is produced. At higher wind

speeds the control system limits the output to the full rated value. [Ref.46:p.24]

5. Power Coefficients

The power coefficient, C_p, of the rotor of a wind turbine system is defined as the ratio of power delivered by the turbine to the total power available in the area of the wind stream subtended by the propeller [Ref.41:p.72 and Ref.43:p.31]. The power coefficient replaces the Betz coefficient in Equation 6-5, as shown below.

$$P = C_p \frac{\rho A V^3}{2} \tag{6-5}$$

where ρ, A, and V are as defined for Equation 6-2.

The actual power coefficient varies with the design of the wind turbine. It is a function of the blade tip speed to free flow wind stream speed ratio. It approaches a maximum value when the ratio is approximately five or six. [Ref.43:p.31 and Ref.46:p.193] The absolute maximum value that the power coefficient could reach is the Betz coefficient, 0.593. However, experimental two-bladed rotor designs have only achieved power coefficients of 0.47 [Ref.40:pp.29-31]. Normally, the relationship between the ratio of blade tip speed to wind speed and the power coefficient is displayed graphically. Such a plot is referred to as a performance curve for the wind machine. Figure 6-6

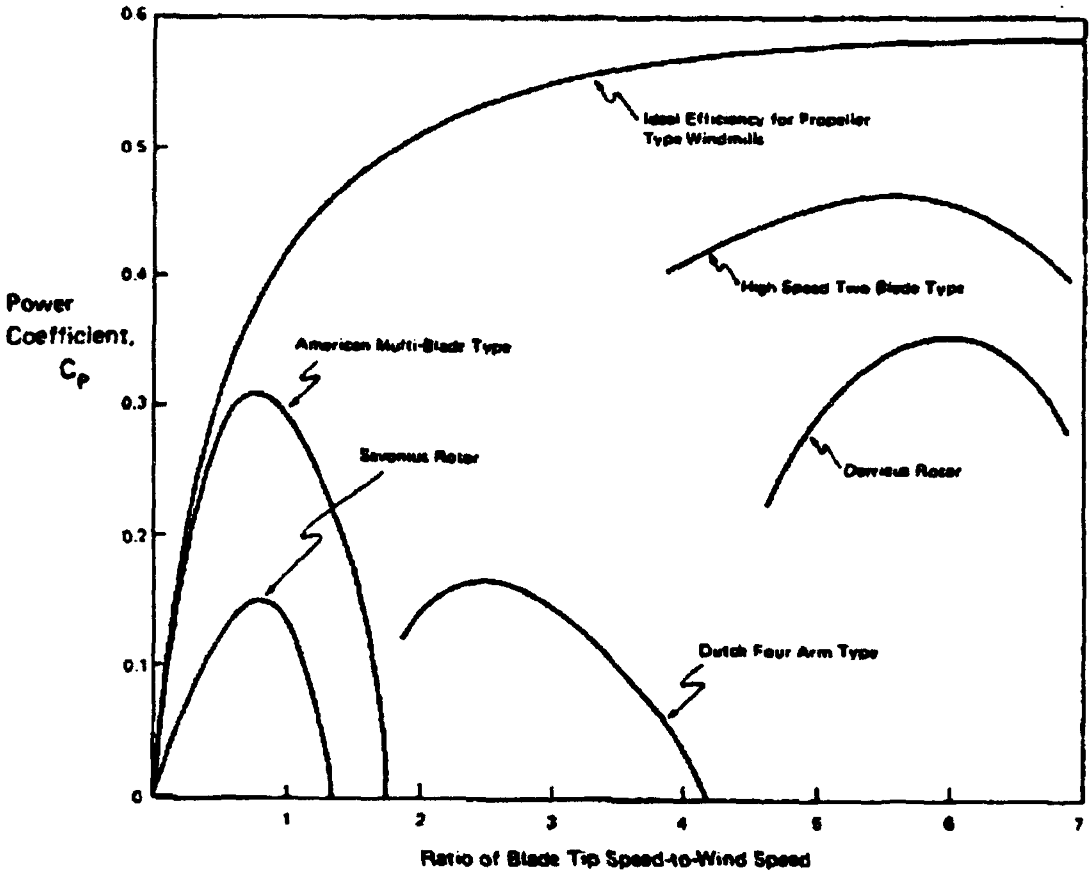

Figure 6-6. Typical Performance Curves [Ref.43:p.32]

illustrates the performance curves for various wind machines designs.

6. Control System

The control system must function and send signals dependent on wind speed. The control system must enable the turbine to operate in an unloaded condition. It must be able to cut-in the generator when the wind speed is high enough for the generator to be able to produce output. Additionally, it must be able to control the blade pitch angle up to the furling point when the wind is above rated speed, when the machine may be shut down. [Ref.46:pp.271-272] The control system must have the following additional capabilities:

- Enable the wind system to operate automatically.
- Keep the turbine aligned with the wind.
- Engage and disengage the generator.
- Protect the turbine from overspeed or damage caused by very strong winds.
- Govern the rotor speed.
- Sense malfunctions in the turbine and alert operators of the need to perform maintenance or repair.

C. ADVANTAGES/DISADVANTAGES OF WIND ENERGY

1. Advantages

Wind energy has some of the same advantages as solar energy. Among the common advantages, as described in Chapter

V, are that wind is a renewable, low cost, cost-effective, and available source.

a. Continuously Renewable Source

Wind is available everywhere and is virtually inexhaustible. It may be more steady and of greater strength in some areas with respect to others, but it is sufficient for use in many applications. There are no requirements on the ability of harnessing the power of the wind, with the exception of the turbine system. There are no limits as to who can use it or where it can be used.

b. Relatively Low Cost

As stated previously, wind energy is considered by many to be a free energy. The only costs associated with an installed wind energy system are limited maintenance and repair expenses.

c. Cost-Effective Source

The utilization of the wind for power generation requires no fuel costs and limited maintenance. Once a system is installed, there are no escalating expenses such as those that occur with fossil-fuelled systems.

2. Disadvantages

There are disadvantages with the use of wind as a power source. However, most of the disadvantages are relatively minor.

a. Unpredictability of the Wind

In general, air is a relatively unstable commodity. Unlike water, wind streams cannot be readily concentrated by channeling or collected to store energy. More importantly, the wind changes direction, speed, and strength with little advance warning.

(1) Minimum Speed Requirements. Annual mean wind speeds of no less than 4 m/s (approximately 8.2 mph) are necessary to make the use wind turbines economically viable. When the wind is not blowing at a fast enough speed, energy must be drawn from storage. As was illustrated in Figure 6-4, as the annual mean wind speed of a location decreases, the annual percentage of winds under 4 mph increases.

(2) Excessive Wind. Regions in which very high winds occur frequently are not suitable for wind power either. All the structural supports must then be designed to withstand the worst wind conditions. Additionally, a wind-driven plant may frequently have to be shut down, resulting in significant losses in power generation and high demands on the energy storage system.

(3) Storage Requirements. As with photovoltaic conversion, the intermittency of the wind poses special problems in storage and distribution. The inherent unpredictability of the wind characterizes wind energy systems. In light of the previous statement that wind speed

and direction can vary considerably throughout the day and night and with seasonal changes, the reliability of wind power is a major problem. However, this problem can be overcome with proper storage of energy. Energy storage is discussed further in Chapter VII.

b. Physical Size of a System

The necessity of tapping a large volume of air to generate power is caused by its low density. Together with the inability to easily concentrate the winds, the low density influences the size of the wind systems. Appreciable power is obtained through the use of large rotors and correspondingly large overall system.

c. Environmental and Biological Effects

Although wind energy systems result in minimal alteration to the environment, some physical damage will be impossible to prevent or predict. Land will be required for the tower and control building, and trees or other obstacles may have to be removed to yield uninterruptible air flow to the turbine.

The wind-driven system effects what is called a zone of influence. This zone of influence encompasses the extent of the system's effects on the physical environment. Studies may be necessary to evaluate the climatological effects of the wind system. [Ref.41:pp.115-117]

The wind system facilities may influence the physical environment to such an extent that the biological environment is also influenced. However, these effects should be minimal. Changes to the local wind stream and increased bird deaths due to collisions with the tower are possible results of a wind power installation. [Ref.43:p.333 and Ref.50]

D. COAST GUARD APPLICATION

1. Power Requirements

Based upon the power specifications as documented in Chapter II, the average power requirements, including 30 percent system losses, for the main communications sites and the microwave relay sites are as follows: 10.97 kWh/day and 0.823 kWh/day for the main communications and the microwave relay systems respectively.

2. Communications Sites in Alaska

Appendix A shows the location of all remote sites located in Alaska that are associated with the Coastal Voice Distress Network, as described in Chapter II.

3. Typical Commercial Wind Turbine

A typical and popular commercially available horizontal-axis 1.5 kilowatt wind turbine (refer to Figure 6-5) has the following specifications:

- Each wind turbine produces 1.5 kilowatts of power at its rated wind speed of 28 miles per hour (mph).

- The turbine-generator can withstand winds up to its maximum design wind speed of 121 mph.
- The turbine starts generating power at its cut-in wind speed of approximately 8 mph.
- The rotor sweeps an approximately 7 m^2 cross-sectional area.

Additional specification data can be found in reference 51.

4. Wind Power in Alaska

A study of Alaskan wind resources and possible applications has been conducted by Wentink [Ref.52]. He determined that most regions have a high wind power potential, especially offshore and in exposed coastal regions. The highest wind power in the Alaska region is along the Aleutian peninsula and island chain between 160° to 172° longitude. Exposed coastal sites and offshore areas of the Aleutians have mean average wind speeds of 7.0 m/sec (16 mph) or greater.

Using Appendix E, the average annual wind speeds for the Alaska sites can be found. The lowest wind speed class for any CVDN site is class 4, which corresponds to wind speeds between 12.6 and 13.4 mph. Using the average annual wind speed and the power curve for a typical 1.5 kilowatt wind turbine (Figure 6-7), a minimum average of approximately 10 kWh/day for each site can be determined. This estimation would be sufficient to charge the batteries for normal system use. However, this is an average per day over an entire year. An in depth analysis of the monthly wind speed is required.

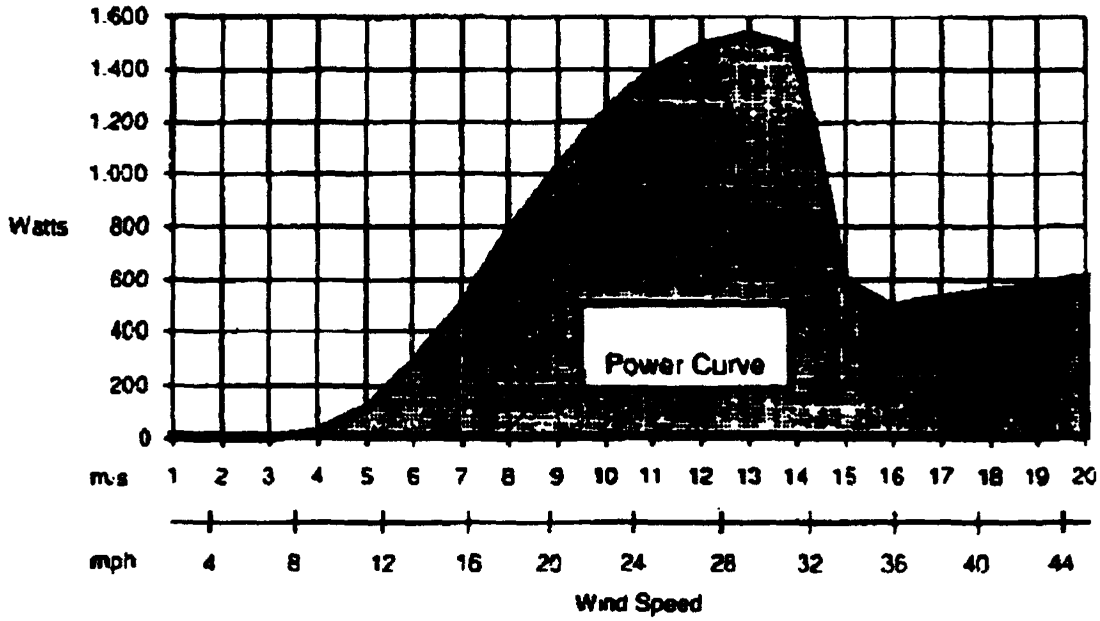

Figure 6-7. Typical Power Curve for 1.5 kW Wind Turbine [Ref.51]

As previously discussed, the highest wind speeds are in the winter months, with speeds dropping off during the summer months. This phenomenon is documented in Appendix D and in Wentink's study [Ref.52]. As an example, wind speeds of above 13 mph (class 5) are typical during the winter months, while class 1 and 2 speeds (below 9.8 mph and 9.8 to 11.5 respectively) are found in the summer months for a site in Kodiak (Figure 6-8). As wind speed decreases, the generated power decreases. When the wind speed falls below the cut-in speed of the typical wind turbine, power generation is negligible. During the days and months of low wind speeds, an alternate or supplemental power generating system is required to augment and complement the wind system.

5. Decision

From the above results, a 1.5 kw wind turbine would be suitable for use in the winter months. However, the typically low speeds of the summer months preclude the use of a wind turbine only system for this application. A more powerful wind turbine could be utilized, i.e., 10 kW, to meet the power demands. However, it would amount to a waste of power and money.

Though the 1.5 kW wind only system is not feasible for year-round use, it could be an attractive solution as a part of a hybrid power system. Wind energy could be utilized during the winter months, while an alternative source could

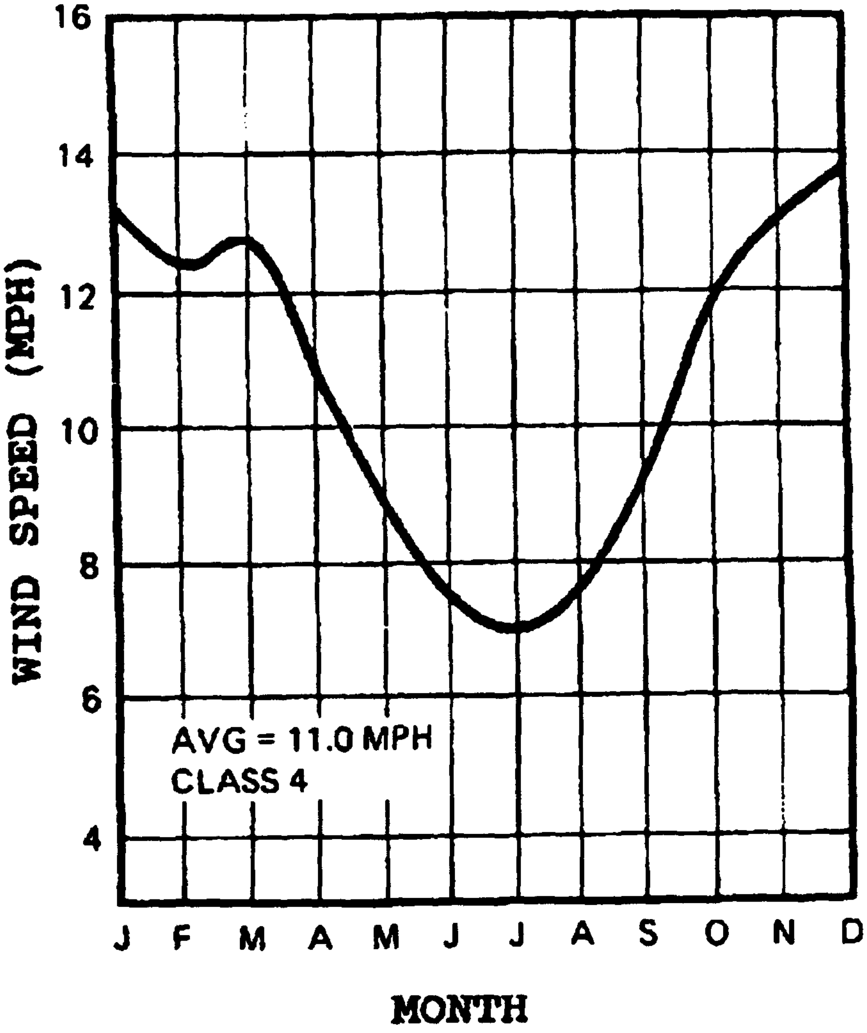

Figure 6-8. Kodiak Monthly Average Wind Speeds [Ref.53:p.119]

produce the majority of the power needed for summer months.

A storage scheme suggested by Karl Bergey [Ref.54] utilizes a combination of a windmill and a water turbine. Water could be pumped into a high reservoir during periods of high wind and the potential energy could then be utilized during periods of low wind. However, with respect to the Alaska application, the freezing weather and lack of suitable hydro sites preclude the possibility of utilizing the potential energy of the reservoir.

The high power potential of the wind turbine during the winter months leads naturally to the selection of the wind turbine in conjunction with another alternative as a hybrid system. The hybrid system solution that will be considered in Chapter VIII is a photovoltaic and wind power system. A photovoltaic power system would be the most suitable partner with the wind system, since solar flux is at its peak in the summer months, while wind speed peaks in the winter. Chapter IV discussed other alternatives that were rejected for use in the Coast Guard application.

An additional requirement to the hybrid system is a battery, charged by the wind-driven generator or from the solar array, in the winter and summer months respectively. A battery and thermoelectric generator backup are obvious requirements, preventing the communications system from being unavailable at any time, thereby increasing the overall system reliability.

VII. STORAGE SYSTEMS

A. GENERAL

It is a requirement of the specification that the power system for the communications station be continuously available [Ref.1]. Although a wind/photovoltaic primary power system may be designed to provide 100 percent of the power required, at times energy delivery will be disrupted. Such factors as extended periods of cloudiness, low winds, or excessively high winds can cause interruptions. Additionally, the photovoltaic array cannot supply power during periods of darkness (night hours or solar eclipse). Furthermore, the power system should have the capability to start up and shut down smoothly. For these reasons, a storage system is required.

A storage system has the capability to readily provide power to the communications site whenever there are periods of low solar intensity, calm winds or excessively high winds. If the wind or solar energy is insufficient to supply the load, or lapses at any moment in time, the storage system must supply the deficit to prevent voltage drops or system shutdown. In the simplest case, a large storage bank fulfills this function as part of its normal means of operation.

The secondary system (thermoelectric generator) could be brought on-line for long-term power production, if the solar/photovoltaic hybrid system fails to provide sufficient power. However, it requires time to start and it does not instantly provide power that is available for use. Money considerations aside, there is always a case for short-term energy storage to reduce the number of thermoelectric start-ups and shutdowns. The optimum size of the storage is uniquely defined for each application. For the Coast Guard application 48 and 96 hours were deemed sufficient for the main communications site and repeater sites respectively [Ref.1].

A storage bank should therefore be incorporated into the design of the overall power system, such that the storage is kept at peak levels. This storage bank will provide for uninterruptible power to the sites in the event of the primary (wind turbine/photovoltaic array) or secondary (thermoelectric generator) power sources failing to meet the power requirements of the communications site.

B. STORAGE OPTIONS

With an adequate storage capacity, a power system can operate independently without connection to a traditional electrical power system. The system can utilize potential, kinetic, thermal, or electrochemical storage methods. [Ref.43:p.41]

1. Potential Energy Storage

Pumped hydro storage is the primary example of potential energy storage. Pumped hydro applications pump water to high storage reservoirs, storing the potential of the water for later use. Although pumped hydro storage is a feasible storage mechanism for most remote operations, it was rejected because of the freezing temperatures. [Ref.1 and Ref.41:pp.105-108]

Another source of potential energy storage is through the use of compressed gasses, such as air, hydrogen or methane. The purpose of a compressed gas storage system is to supplement the power supply through the expansion of the compressed gas, whenever the demand exceeds the generated power of the wind turbine and/or the photovoltaic array. Unfortunately, this system has demonstrated only a few minutes of storage capability at an acceptable cost, not the hours that are required by the specification. Additionally, large storage facilities (e.g., caverns) are required for large-scale compressed gas storage. [Ref.36:p.236 and Ref.55:p.184]

2. Mechanical Energy Storage

Flywheels are mechanical devices that rapidly spin in an evacuated chamber. They have achieved significant storage capacities and have demonstrated the potential for use as long-term storage devices [Ref.44:p.163]. However, this storage method was rejected for the following reasons:

- Remote area maintenance and reliability requirements have not been demonstrated.
- Significant standing losses are incurred due to the necessity of continuous flywheel rotation.
- Low temperature environment studies would be necessary to study the feasibility of the flywheel utilization.
- The system would incur high monetary costs. [Ref.55:p.184].

Flywheel energy storage is undergoing continuous research in both the United States and United Kingdom, especially with regard to utilization in the space environment where the near zero pressure provides the vacuum required for efficient flywheel operation [Ref.56:p.218]. Although practical commercial-scale units have yet to be demonstrated, the flywheel has the ability to store up to 80 percent of the energy input.

3. Thermal Energy Storage

Thermal energy storage can be accomplished using either of two basic methods: by means of sensible-heat and by means of latent-heat. Energy can be stored whenever a material is heated, melted or vaporized. Upon reversal of the process, heat is given off, and energy is available for use.

Sensible-heat storage stores energy by raising the temperature of a material. The density and specific heat of the material have significant effects upon the efficiency of this method of energy storage [Ref.41:p.109].

Forcing a material to undergo a phase change (solid to liquid or liquid to gas) is an energy storage technique known as latent-heat storage. Unlike sensible-heat storage, there is no temperature change in latent-heat storage. [Ref.41:p.109] Latent-heat storage systems take advantage of the heat of transition during a material's phase change (e.g., from water to steam).

Both latent-heat and sensible-heat storage systems were dropped from consideration because the design of the storage bank would require the addition of some type of heat engine.

4. Electrochemical Energy Storage

Electrochemical storage is the most widely investigated and widely utilized storage technique. Storage batteries can store or deliver energy depending upon the electrochemical reactions taking place at the electrodes in the electrolyte [Ref.41:p.104]. Primary and secondary are the two types of batteries that could be utilized as part of the storage system.

a. Primary Battery

There are three subtypes of primary cells, as described below.

- A primary active battery, that is capable of discharging all of its energy a single time. After the single discharge, the battery is useless.

- A reserve primary battery, which has the same characteristics as the primary active battery, with one exception. A long shelf life is obtainable because the electrolyte is stored away from the electrodes until it is time to activate the battery.

- A thermal primary battery, which has the same characteristics as the reserve primary battery, except that it operates at high temperatures, typically for only a few minutes. [Ref.57]

Although primary batteries can store energy, they should not be used in the storage system. Primary cells cannot be recharged because the chemical action in the cells cannot be reversed. As the communications sites are remotely located, it would be unjustifiably expensive to replace the storage system every time the storage system is activated.

b. Secondary Battery

The secondary battery is by far the most common method of storing the electric energy generated by solar and wind-generator power systems. Secondary batteries are rechargeable, and as such, they bridge periods of insufficient insolation and wind. Through proper recharging, the chemical actions occurring during discharge can be reversed. The secondary cells can be restored to their original condition and made ready to discharge all of their energy. It can be charged and recharged via the wind-powered generator or the photovoltaic array. Any excess power generated by the hybrid system, above the required power for the load, is used to charge the battery storage system up to full capacity.

C. RECHARGEABLE STORAGE SYSTEM CHARACTERISTICS

The wind does not always blow and the sunshine does not always reach the solar array when electricity is being used. Consequently, batteries are extremely useful to store electricity until it is needed. As stated earlier, a secondary battery can be recharged and discharged numerous times. The number of times depends upon such factors as construction, use, and care.

1. Construction

The construction of a lead-acid battery (Figure 7-1) is briefly discussed in this section. Other types of batteries have similar construction. The major differences being the material that the plates and separators are made of.

A battery is made up of individual cells. Each cell is made up of a quantity of positive plates, negative plates and separators. The plates are made of lead compounds (for a lead-acid battery). The plates are immersed in an electrolyte, also known as battery acid, composed of a sulfuric acid (H_2SO_4) and distilled water (H_2O) mixture. There is a separator between each plate, keeping the positive and negative plates away from each other. Separators are typically made of porous (to allow the electrolyte to pass) nonelectrical materials (e.g., rubber, wood, or plastic). The lead-acid battery is the most common and generally the lowest cost battery. [Ref.47:p.103] A group of negative and positive

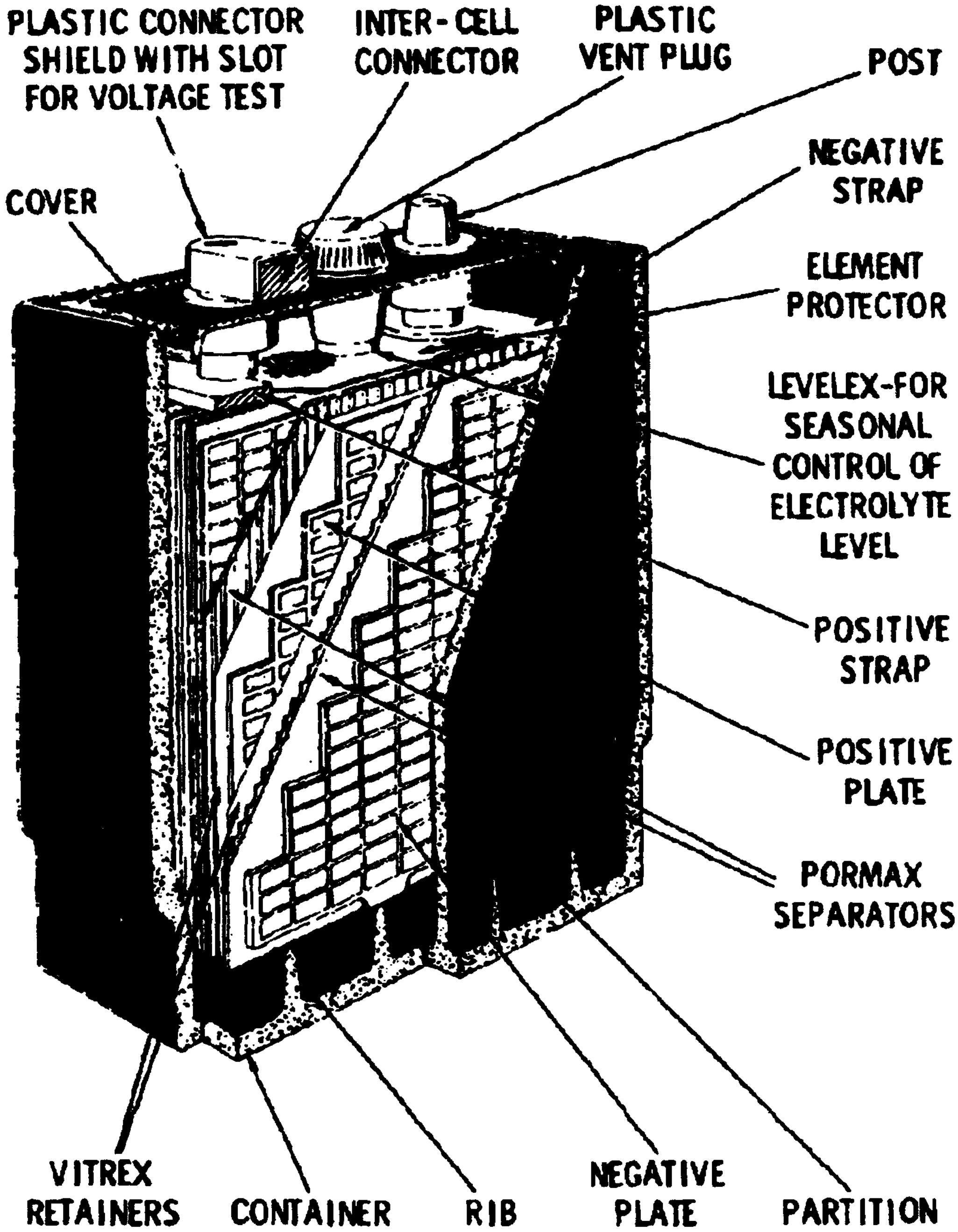

Figure 7-1. Lead-Acid Battery [Ref.58:p.99]

plates along with the necessary separators makes up an element of a cell, as shown in Figure 7-2. A cell consists of an element immersed in a container of electrolyte. A typical cell of a lead-acid battery will deliver a nominal 2 volts. Therefore a battery is constructed of several 2 volt cells, connected in series, to increase the battery voltage. Series connections will be discussed later in this chapter. [Ref.35:pp.48-49]

2. Storage Capacity

The storage capacity of batteries is assessed in two ways. These are ampere-hour capacity and the total kilowatt hours of energy that can be stored. They are described below.

a. Ampere-Hour Rating

One measure of battery storage capacity is ampere-hour (a-h) rating. Ampere-hour rating is a description of the amount of current (amperes) that a battery can deliver, multiplied by the time (hours) that it can deliver that current. For example, a 100 a-h battery can approximately deliver 25 amperes of current for four hours, 50 amperes for two hours, 100 amperes for one hour, or many other combinations. [Ref.47:p.107]

(1) Current Demand Effect. The preceding paragraph provides theoretical estimates of the ampere-hour capacity with respect to the current drawn from the battery. However, practical experience has shown that large loads drawing high

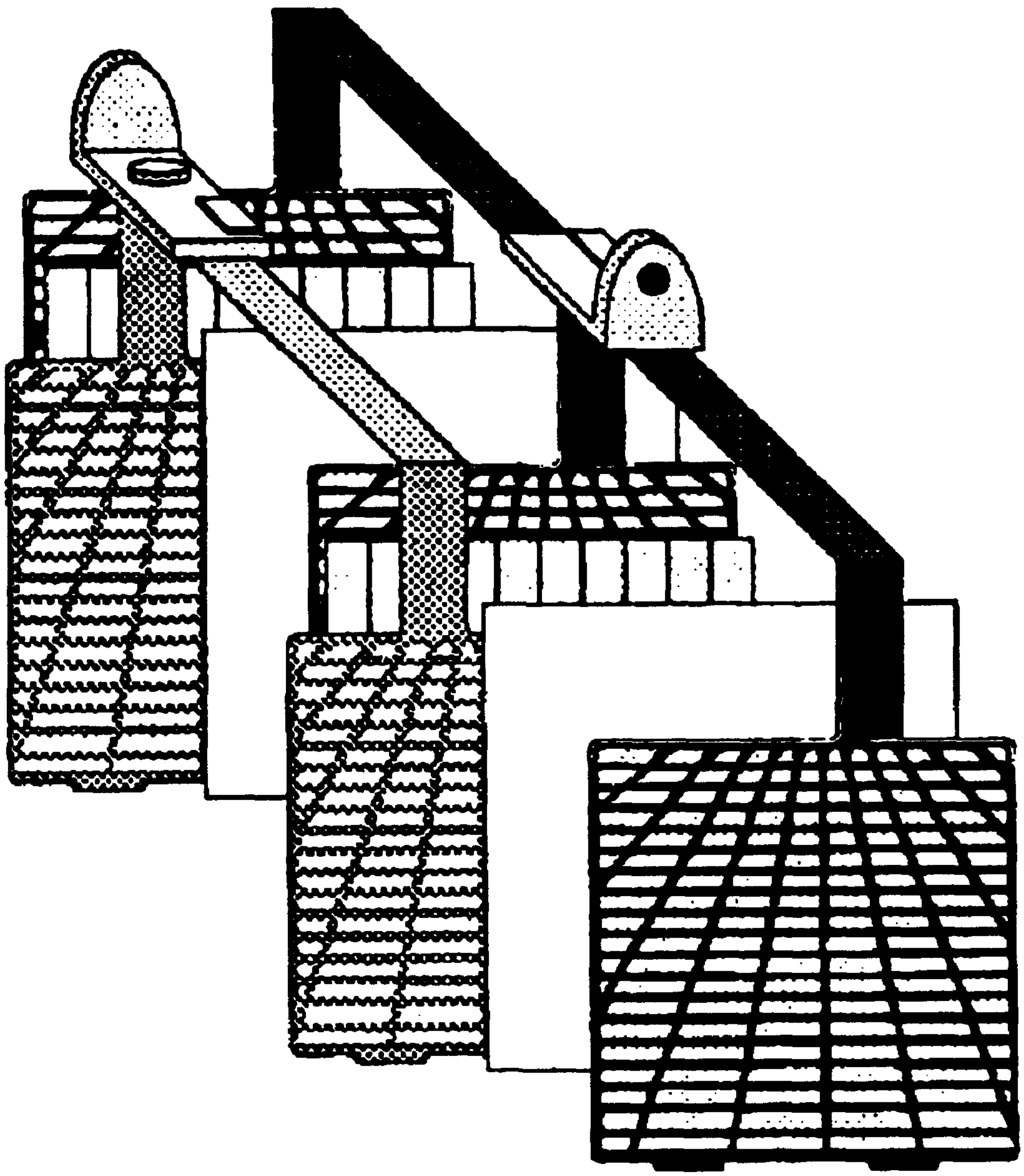

Figure 7-2. Element Construction of a Lead-Acid Battery [Ref.35:p.49]

current and small loads drawing low current discharge faster and slower than the theoretical estimate respectively. The curves of Figure 7-3 graphically explain the relationship between delivered current and ampere-hour capacity. [Ref.35:p.45 and Ref.58:pp.102-103]

(2) Temperature Effect. The temperature of the battery and surrounding area also significantly affects the ampere-hour capacity. Battery capacity is considered to be 100 percent at approximately 80 degrees Fahrenheit (°F). In other words, a battery that is rated at 100 a-h has a 100 a-h capacity at 80°F. As shown in Figure 7-4, at freezing (32°F), the capacity of the battery at the 24 hour rate is approximately 85 percent of its maximum [Ref.35:p.46]. As temperature is decreased, battery capacity is decreased. Higher temperatures result in a somewhat higher capacity than theoretical. "Ideally a battery should be kept between 60° and 85°F for longest life and greatest capacity [Ref.47:p.114]."

b. Kilowatt Hour Storage

Another measure of capacity is the total amount of kilowatt hours (kWh) of energy that can be stored. It can be determined by multiplying the voltage supplied by the battery with the ampere-hour rating to give the answer in watt hours. Dividing that by 1,000 yields the answer in kilowatt hours. Continuing with the 100 a-h battery from above, and assuming

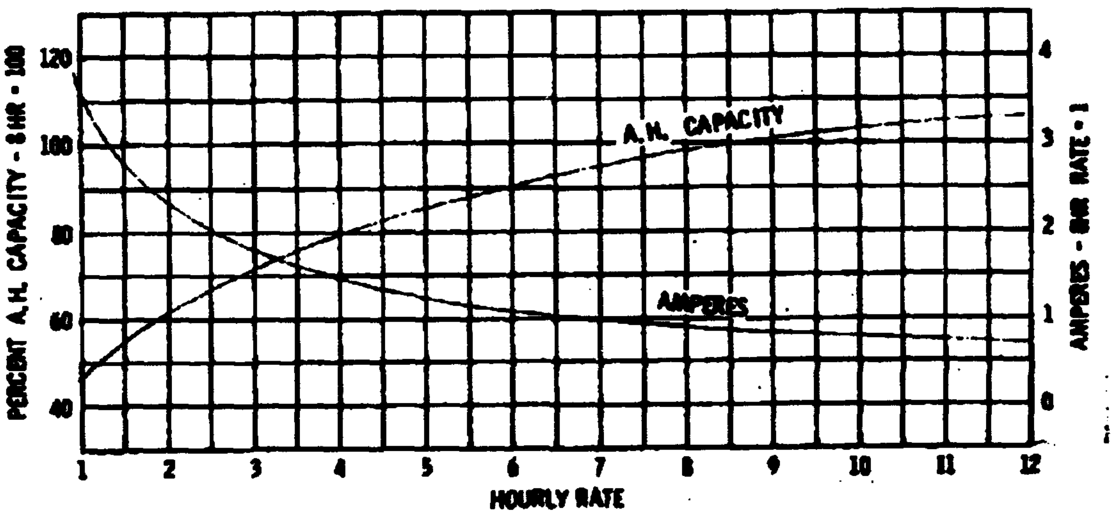

Figure 7-3. Influence of Current Demand on Ampere-Hour Capacity for 100 a-h Battery [Ref.58:p.102]

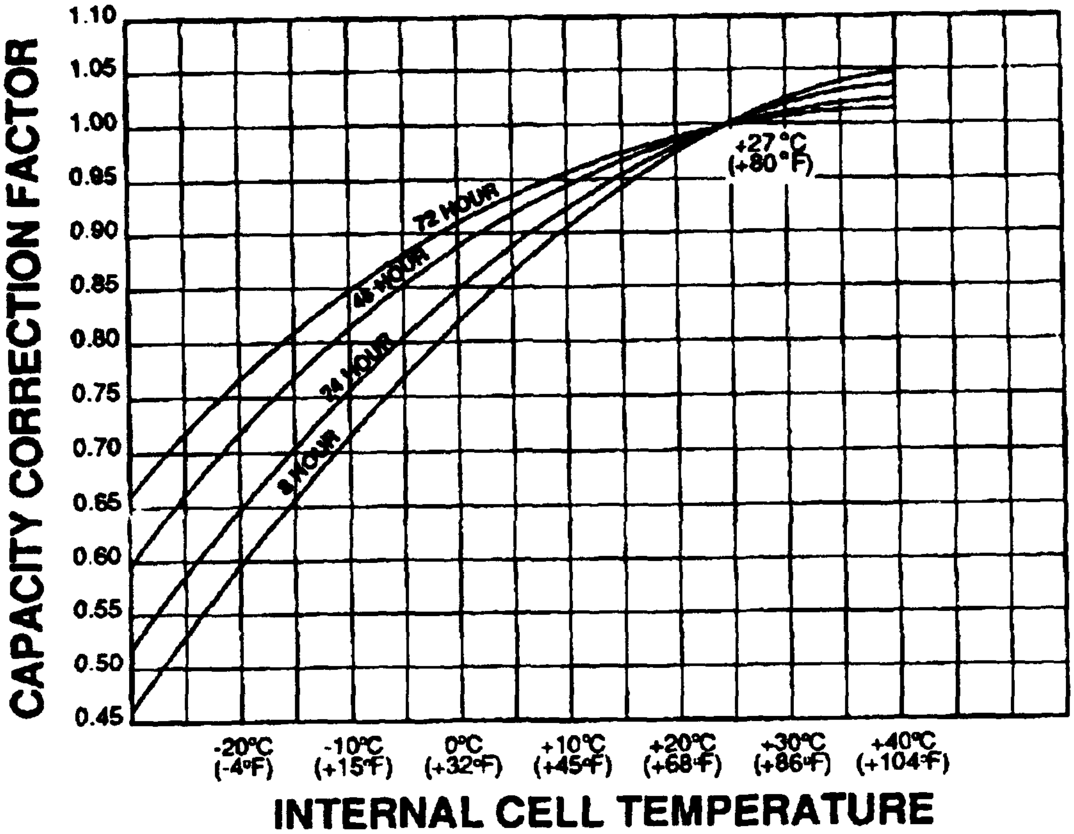

Figure 7-4. Battery Capacity at Different Temperature [Ref.35:p.46]

it is a 12 volt battery, it can store and deliver 1.2 kilowatt hours of energy. [Ref.47:p.107]

c. Battery Weight

Although not an appraisal technique in the strictest sense, battery weight is an indication of storage capacity. The amount of lead in a battery is an indication of its capacity and expected lifetime. For example, "a 50 pound electric vehicle battery rated at 225 a-h will not last as many years as a 150 pound industrial truck battery with a 225 a-h rating [Ref.47:p.107]."

3. Battery Connections

An interconnected group of batteries, known as a battery bank, makes up a storage system to provide the desired voltage and ampere-hour storage capacity. For example, the typical 12 volt car battery (13.2 volts in actuality) consists of six cells, each with 2.2 volt nominal voltage. [Ref.47:pp.102-103] Batteries can be connected in series, parallel, or in a series-parallel arrangement, as shown in Figure 7-5.

a. Series

Batteries are connected in series to increase the voltage that is made available by the storage bank. Uniting batteries in series describes the procedure whereby the positive terminal of one battery is connected to the negative terminal of the next one. The positive terminal of that

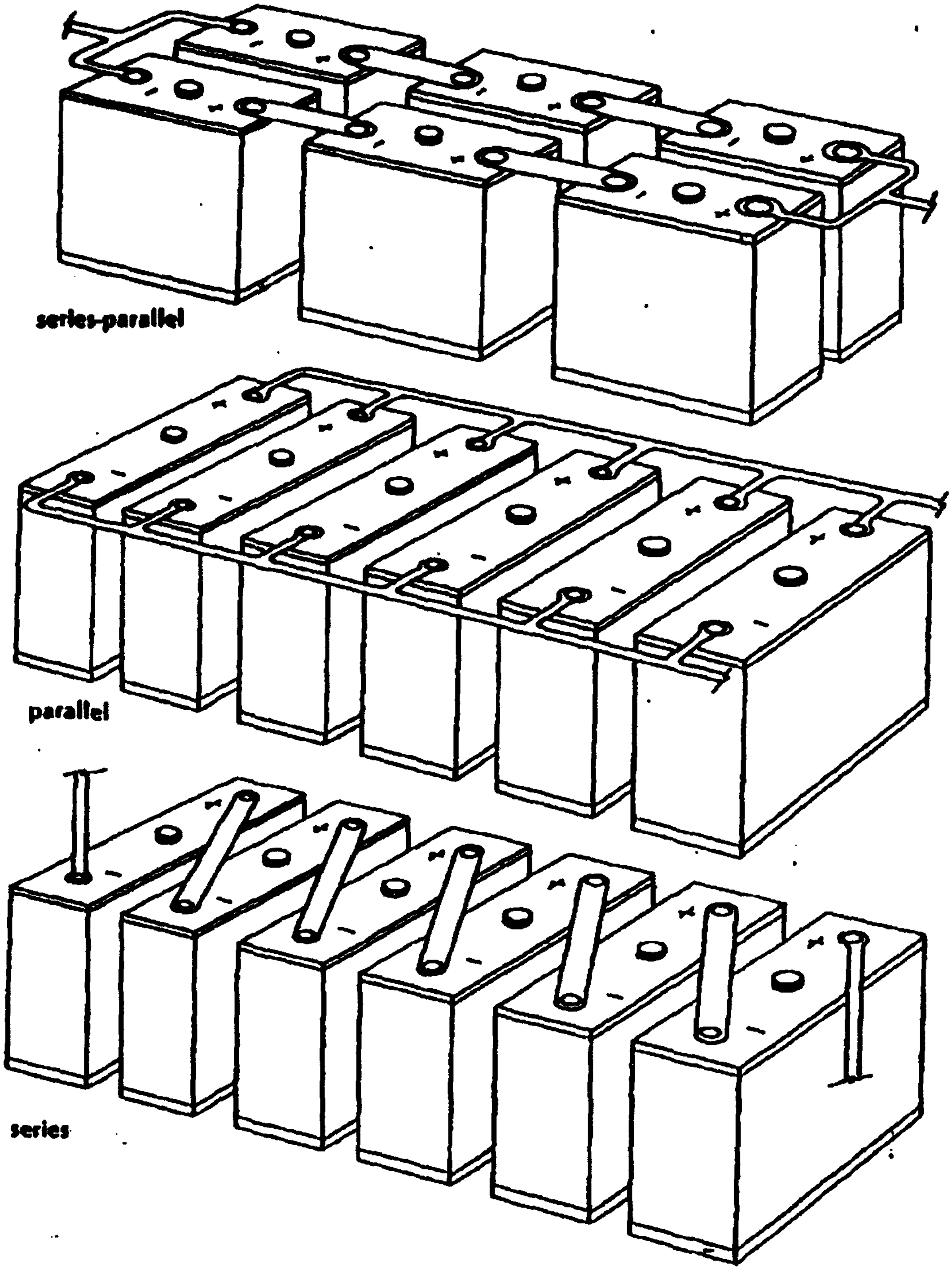

Figure 7-5. Battery Connections [Ref.47:p.110]

battery is then connected to the negative terminal of the next battery in line.

The voltage of the battery bank is the sum of the individual battery voltage making up the series arrangement. The series arrangement does not affect the ampere-hour rating of the bank. However, the kilowatt hour rating of the bank increases due to the increased bank voltage. As an example, consider 12 volt batteries with a 100 a-h rating. If three of the 12 volt batteries are connected in series, the total voltage of the bank would be 3 x 12, or 36 volts. The ampere-hour rating would remain the same, but the total kilowatt hour that would be available would be 36 x 100/1000, or 3.6 kWh. [Ref.47:p.109]

Only batteries that have the same ampere-hour capacity should be connected in series. When mixed capacities are involved in series connections, there is an increased probability of charging problems occurring (i.e., the largest capacity battery will not be charged up to its fullest, and the smallest will be overcharged). [Ref.47:p.111]

b. Parallel

Batteries should be connected in parallel to increase the ampere-hour capacity of the battery system (the current increases, as does the ampere-hour capacity; however the voltage remains the same). As is illustrated in Figure 7-5, the negative terminals of all the batteries in the bank are

tied to the same bus, while the positive terminals are connected to a different bus. The parallel configuration is analogous to the procedure followed when jump-starting a car. [Ref.47:p.111]

Batteries having the same voltage must be used when connecting up a battery bank utilizing a parallel arrangement. Battery voltages will equalize (higher voltage batteries will discharge themselves and will eventually reach the level of the lowest voltage battery in the bank) if this recommendation is not followed. [Ref.47:pp.111]

c. Series-Parallel Arrangement

A series-parallel arrangement is a grouping where two or more series strings of the same voltage are connected in parallel. For example, two 16 volt, 100 a-h capacity, series strings are connected in parallel. Each string can store and deliver 16 x 100/1000, or 1.6 kWh. Together, the two strings are equivalent to a 16 volt, 200 a-h string, capable of delivering 16 x 200/1000, or 3.2 kWh. Series-parallel arrangements are not typically used, as weak cells in one string tend to pull down cells in the other string(s). However, isolating diodes in series with each string will prevent the discharging of one string into another string. [Ref.47:pp.111-112]

4. Battery Lifetime

During sunny periods (high insolation) and windy periods, batteries store the energy generated by the photovoltaic array and the wind-powered generator system respectively. They supply the power whenever the photovoltaic array and the wind system cannot supply enough power to meet the demand. [Ref.35:p.44] The number of cycles, depth of discharge, undercharging, and overcharging are factors that affect battery lifetime. Lead-acid batteries are discussed in the next four subsections unless otherwise noted.

a. Number of Cycles

When batteries are storing energy, they are charging. While they are supplying power, they are discharging. A cycle is a period that includes a battery discharge and a battery charge. After a large number of cycles, the battery starts losing the ability to charge. Hence, batteries have a finite lifetime. [Ref.47:p.108] The lifetime of a battery is measured by the number of cycles it can undergo [Ref.41:p.104-109].

b. Depth of Discharge

The total ampere-hour capacity that is used during a cycle is known as the battery's depth of discharge. Typical shallow cycle batteries are designed to discharge from ten percent to 25 percent of their capacity each cycle, while deep cycle batteries are designed to discharge up to 80 percent of

their capacity. Batteries that undergo a higher average depth of discharge will have a shorter lifetime (last for fewer cycles) than batteries with a shallower depth of discharge. Figure 7-6 depicts the relationship between the average depth of discharge and the lifetime (number of cycles) of a deep cycle lead-acid battery. [Ref.35:p.47] It should be noted that batteries should not be discharged below certain levels. For example, if a purpose of the battery is to start a piece of equipment, it should not be discharged below the starting voltage of the equipment.

c. Undercharging

Two effects can result from a battery that has been undercharged. If a battery remains undercharged and is not charged to its full capacity, its actual capacity may be diminished. For example, as a consequence of not being charged past 80 percent of capacity, a battery could lose up to 20 percent of its original capacity. A second consequence of undercharging is that recharging may become more difficult if a battery remains severely undercharged for long periods of time. At a minimum, lead-acid batteries should be fully charged at least once per month. [Ref.47:p.108]

d. Overcharging

Unlike undercharging, overcharging physically damages the positive and negative plates of the battery. Continuing to charge a battery past its full capacity forces

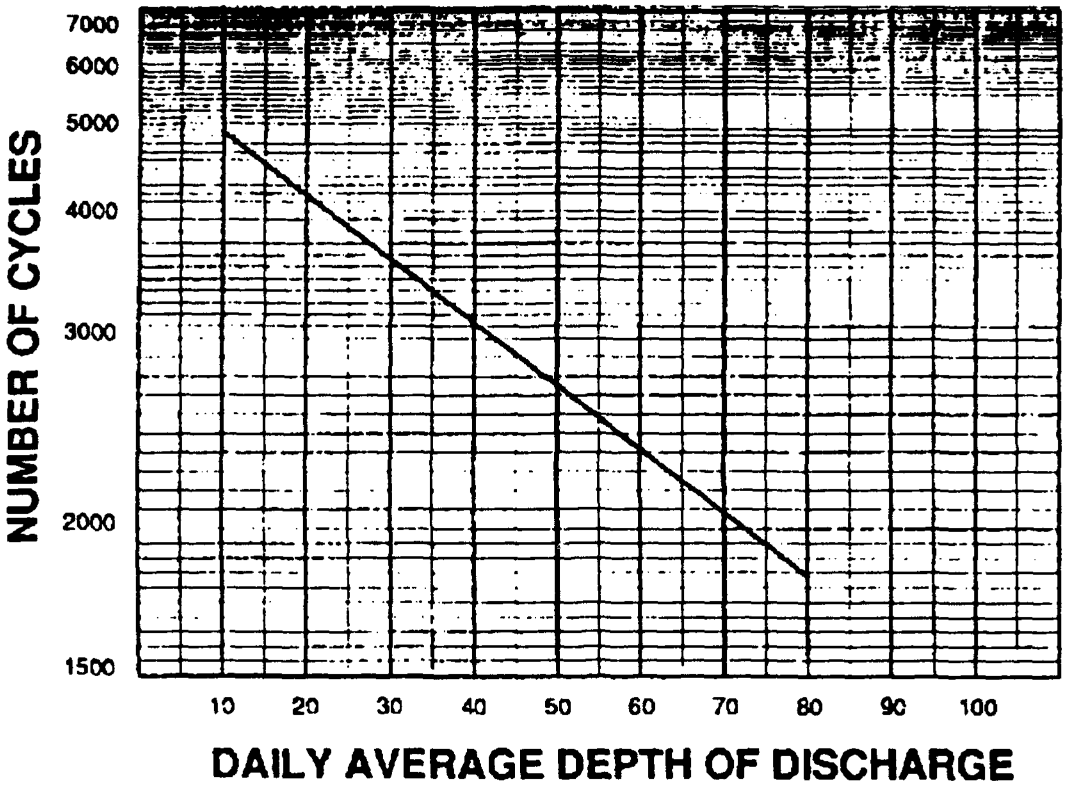

Figure 7-6. Number of Cycles for Different Discharge Depths of a Deep Cycle Battery [Ref.35:p.47]

the electrolyte to lose water which increases the concentration of sulfuric acid. The water is electrolyzed into hydrogen and oxygen bubbles, which may loosen and consequently damage the plates. The increased concentration of acid can cause plate corrosion. Severe overcharging results in the buckling of the plates and the destruction of the battery. [Ref.47:p.109]

Overcharging is normally prevented through the use of a battery charging regulator. A regulator decreases the charging rate to a trickle charge as the battery nears full capacity.

Cells within a battery may develop different capacities over a period in which a number of charge and discharge cycles occur. These differences are caused by sulfation and imbalances in the sulfuric acid concentration throughout the entire battery. If not corrected, these differences may worsen and lead to cell and battery damage. The differences may be corrected by performing an equalizing charge which is an intentional slight overcharge of the battery, bringing weakened cells back into the normal specification range. An equalizing charge should be performed at least semiannually. [Ref.47:p.109 and Ref.59:p.10]

5. Measuring/Monitoring the State of Charge

The state of charge of the battery may be measured using a hydrometer or it may be monitored using a voltmeter.

a. Hydrometer

A hydrometer can measure the specific gravity of the battery electrolyte. The measurement of specific gravity with a hydrometer yields the "... true state of charge of a battery ... [Ref.47:p.114]"

Specific gravity is the weight ratio of equal volumes of electrolyte and water. The specific gravity of water is 1.000. Sulfuric acid has a specific gravity of 1.840 (an equal volume of sulfuric acid has a weight that is 1.840 times greater than water). Consequently, the electrolyte of a lead-acid battery, sulfuric acid and water, will always be between 1.000 and 1.840. [Ref.47:pp.112-115]

When a lead-acid battery is fully charged, the specific gravity of the electrolyte is approximately 1.300. When the battery is fully discharged, the value of the specific gravity is 1.110. For 25, 50, and 75 percent of full charge, the specific gravity of the electrolyte is 1.210, 1.240, and 1.270 respectively. As the battery is charged the specific gravity increases. [Ref.47:pp.115]

b. Voltmeter

The voltage of a battery increases as a battery undergoes charging, much like the specific gravity increases. The utilization of a voltmeter, albeit a simple method to obtain battery voltage, does not give an accurate measure of battery charge. Using a voltmeter and measuring the voltage

of a fully charged cell, a reading will be obtained that falls between 2.1 and 2.2 volts, depending on the specific gravity of the electrolyte. A voltmeter will read 1.75 volts from a completely discharged cell. [Ref.47:p.115 and Ref.35:p.54] Experience has demonstrated that it is difficult to obtain an accurate picture of a battery's charge when using a voltmeter. Nonetheless, a voltmeter is effective in determining whether a battery is at a full or low state of charge. [Ref.47:pp.116-117]

6. Freezing Point

There is an important aside to measuring the specific gravity of the electrolyte. As it increases, the temperature at which a battery will freeze (freezing point) decreases. This is important, especially in cold climate areas (such as Alaska). Hence, the electrolyte in a battery acts as an antifreeze (which is why the car battery does not freeze unless it is completely discharged).

When fully charged, a typical lead-acid battery will not freeze until the temperature falls to approximately -95°F. However, if the battery is only 50 percent charged, it can freeze at -50°F. [Ref.35:pp.53-54 and Ref.47] The battery used for an application should not be allowed to be discharged below a level at which the specific gravity of the electrolyte indicates that the battery would freeze in the ambient temperature [Ref.47:p.108].

7. Advantages and Disadvantages of Rechargeable Batteries

Secondary batteries have some distinct advantages and disadvantages. Among the advantages, besides being rechargeable, are:

- Batteries are a well proven and readily available technology.
- Batteries can provide instantaneous power whenever wind or solar energy is insufficient.

Among the disadvantages are:

- Battery costs are extremely high.
- Batteries have a finite lifetime.
- Batteries require special care and maintenance.

D. STORAGE SYSTEM FOR THE COAST GUARD APPLICATION

As was calculated in Chapter II, the power required for the main communications sites and the microwave relay sites is 10.97 kWh/day and 0.823 kWh/day respectively. The specification [Ref.1] requires a storage bank capable of providing a 48 hour battery supply for the main sites and a 96 hour supply for the relay sites. In addition, the system must operate in temperatures from -20 degrees Celsius (°C) to 40°C, which corresponds to -4°F to 112°F.

1. Storage Decision

If the supply of electricity is to be maintained continuously, a storage system, charged from the wind-driven

generator or from the solar array, in the winter and summer months respectively, is an obvious requirement. It is also obvious that the storage system is necessarily constructed of rechargeable batteries. The principal responsibility of the storage system is to take over the load immediately when the primary power source fails to provide the required power. The storage system must continue to supply the power to the load until either the normal power supply is restored or a secondary system picks up the load. A secondary function is to supplement the primary system on days of less-than-average wind power or solar flux.

As described in Chapter VI, the wind energy is intermittent in most locations. Consequently, there may be the need to store wind energy over long periods of time, perhaps up to ten days or more. Additionally, extremely cloudy periods can significantly affect the solar energy collection of the photovoltaic array for many days. However, the storage requirements can be significantly reduced when there is no one sole source of power. As previously discussed, the primary power system will be a hybrid system, consisting of a wind turbine and a photovoltaic array. The storage requirement for the entire system is not as stringent as for a solo wind or photovoltaic system. The storage requirements for the main sites and relay sites are as previously stated.

2. Rechargeable Batteries Under Consideration

The two most popular types of rechargeable batteries in use in storage systems are nickel-cadmium (NiCd) and lead-acid batteries.

a. Nickel-Cadmium Batteries

Nickel-Cadmium batteries are of the family of alkaline batteries. Alkaline storage batteries are rechargeable and utilize an electrolyte consisting of a solution of potassium hydroxide. The construction of a NiCd cell (Figure 7-7) is similar to that of the previously discussed lead-acid cell. However, the positive and negative plates are made of nickelic hydroxide and metallic cadmium respectively. The typical NiCd cell can provide a voltage of 1.2 volts [Ref.60:pp.324-331]. Although highly reliable, NiCd batteries are extremely expensive and their high cost prohibits large scale utilization [Ref.36:p.239].

b. Lead-Acid Batteries

The lead-acid battery as depicted in Figure 7-1, is readily available and comparatively inexpensive (compared to NiCd batteries). It is the most common wind/solar energy storage device. The typical cell in a lead-acid battery can deliver a nominal 2 volts. If lead-acid batteries are discharged slowly and overcharging is avoided as much as possible, they may have a lifetime of 20 to 30 years [Ref.36:p.239 and Ref.58:p.104]. Conventional technology

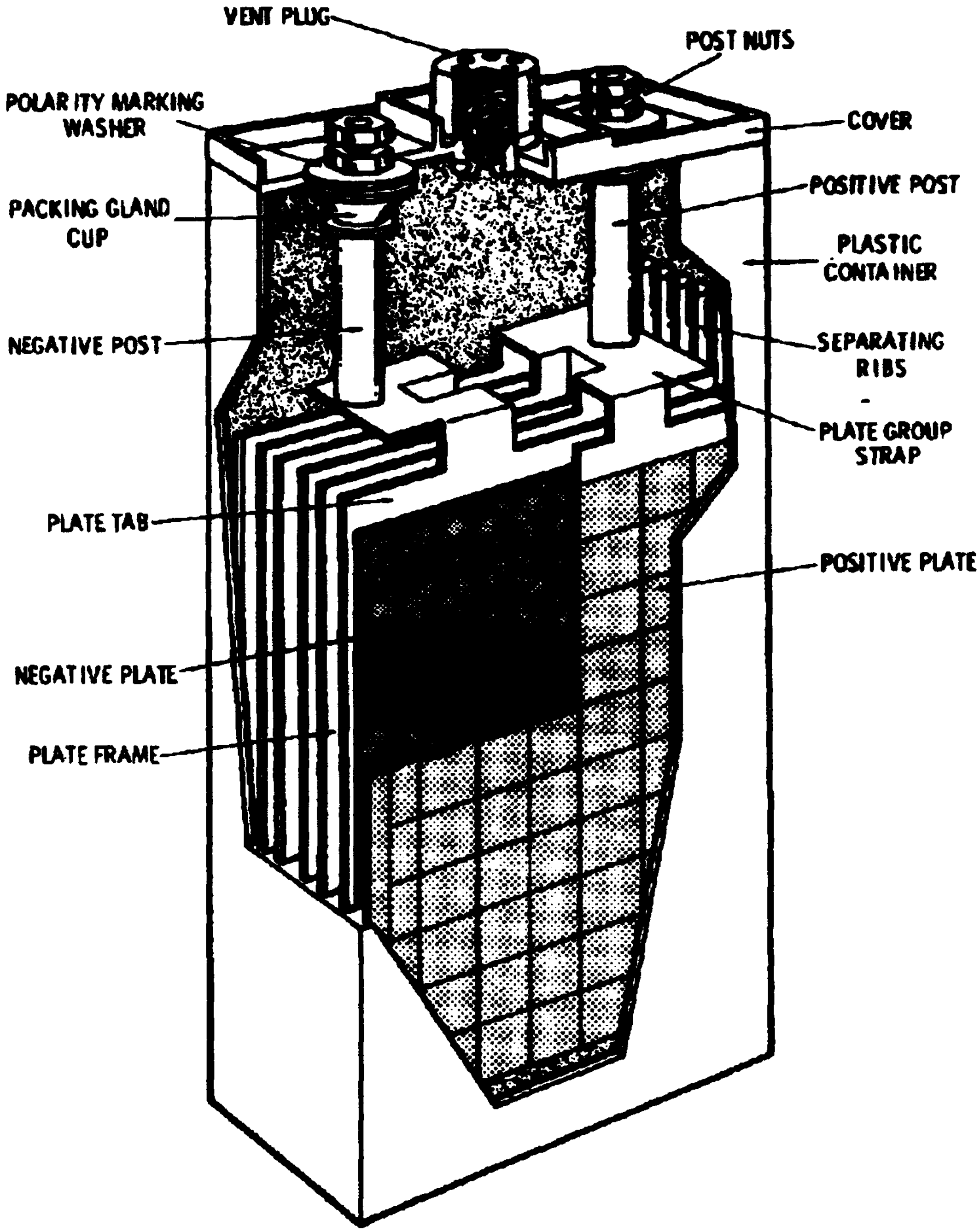

Figure 7-7. Nickel-Cadmium Battery [Ref.58:p.122]

dictates the use of a lead-acid battery storage bank whenever possible. The construction of a lead-acid battery was discussed in Section C.1.

3. The Coast Guard System

This section will discuss the specifics of the storage system selected for the Coast Guard application in Alaska. The system will be composed of lead-acid secondary batteries.

a. Required Kilowatt Capacity

As previously stated, the main sites require 10.97 kWh/day for 48 hours (two days), or 21.94 kWh. The microwave relay sites require 0.823 kWh/day for 96 hours (four days), or 3.292 kWh.

b. Required Ampere-Hour Capacity

As discussed in Chapter II, the main sites are required to provide power at 24 volts, while the relay sites provide power at 12 volts. The number of ampere-hours required can be determined by dividing the required kilowatt capacity by battery voltage and multiplying the result by 1,000. For the main sites, 914.2 a-h, and for the relay sites, 274.3 a-h are required. This includes the 30 percent losses discussed in Chapter II.

To ensure that the storage system is not discharged below 50 percent, the required ampere-hour capacities should be doubled. Therefore, the main site requirements dictate

approximately 1,829 a-h, while the relay sites require about 550 a-h.

c. Size/Layout of the Storage System

As determined by the two preceding sections, the main site storage system requirements can be satisfied by a 24 volt battery bank rated at 2,000 a-h. This translates to a system consisting of 20 12 volt, 200 ampere-hour deep cycle lead-acid batteries in a series-parallel arrangement (ten parallel strings each with two 12 volt batteries in series).

For the microwave sites, a smaller system consisting of a 12 volt battery bank rated at 600 a-h will fulfill the requirements. The microwave storage system will incorporate three 12 volt, 200 a-h deep cycle lead-acid batteries connected in a parallel arrangement. Twelve volt lead-acid batteries rated at 200 a-h that can operate in the temperature band required are commercially available [Ref.47:p.107].

VIII. HYBRID SYSTEM FOR COAST GUARD APPLICATION

hy·brid \'hī-brēd\ n [L *hybrida*] (1601) ... 3 a: something heterogeneous in origin or composition: composite <artificial ~s of DNA and RNA>; *also*: something (as a power plant, vehicle, or electronic circuit) that has two different types of components performing essentially the same function. [Ref.61:p.175]

A. GENERAL

As was discussed in Chapters V and VI, neither a photovoltaic only system nor a wind only power system is capable of meeting the year-round power requirements for a main communications site. A wind only system (with appropriate battery storage backup as was discussed in Chapter VII) would be able to handle the relatively low power microwave relay site load. However, a four panel photovoltaic array could be utilized in conjunction with the wind turbine to ensure the power requirements in the low wind summer months are fulfilled, as was discussed in Chapter V. This chapter will discuss a typical hybrid power system for a main communications site with respect to the specific Coast Guard application in Alaska.

Even though a primary power system may be designed to provide 100 percent of the power required, such factors as extended periods of cloudiness, low winds, or excessively high winds can significantly disrupt the energy delivery. The

storage system discussed in Chapter VII provides power during the disruptions. However, if long-term disruptions occur, a secondary power system would be required as the storage system has a finite capacity.

B. SECONDARY POWER SYSTEM

The communication system is required to be operational 24 hours a day, 365 days a year [Ref.1]. The power system must also operate 24 hours a day, 365 days a year. The major problem is in ensuring the continuity of the supply of electrical power. While the storage system provides for temporary disruptions in power (i.e., darkness or extensive cloud cover for the solar array or short calm periods for the wind power system), the capacity is finite. Consequently, a secondary power system is necessary.

The most cost-effective method for backing up the primary power system is through the use of the local utility power system. However, since there is no access to a local utility power system, some other method of backup must be used.

Thermoelectric generators were the previous power systems located at the sites. As was discussed in Chapter III, they are highly reliable. They can be started remotely via a system operator request or they can come on line if a low battery capacity signal is received. Accordingly, thermoelectric generators should be used as the secondary power system, available to backup the designed hybrid system.

C. STORAGE

The storage system to be utilized with the primary power hybrid system and thermoelectric generator secondary system is as discussed in Chapter VII.

For the main site, the storage system will consist of 20 12 volt batteries each rated at 200 ampere-hours connected in a series-parallel arrangement. For the relay sites, the storage system will incorporate a parallel group of three 12 volt batteries rated at 200 a-h each.

The storage system will provide temporary backup power to the main and relay sites whenever the wind and solar energy is insufficient to meet the load requirements. However, since the capacity of the storage systems is finite, as each system approaches 50 percent capacity limit, it will signal the backup thermoelectric generator to pick up the load requirements.

The rechargeable storage bank can be charged and recharged via the wind-powered generator or the photovoltaic array. Any excess power generated by the hybrid system, above the required power for the load, is used to charge the battery storage system up to full capacity.

D. TYPICAL HYBRID POWER SYSTEM DESIGN

A goal of this thesis was to design a power system capable of utilizing the natural energy at remote sites to supply the electrical power required for remote site loads. As was shown

in Chapters V and VI, neither a wind only system nor a photovoltaic array only system could achieve the goal. Appropriately, the primary power system should be hybrid in nature, consisting of a photovoltaic array component (Chapter V) in conjunction with a wind-powered generator component (Chapter VI). This was considered to be an attractive (though not the only) solution to meet the requirements of the design. The backups (thermoelectric generator and battery storage bank) to the primary system have been previously discussed. A typical hybrid power system design is illustrated in Figure 8-1.

1. Wind-Powered Generator Component

As was discussed in Chapter VI, a 1.5 kW wind turbine generator is sufficient to meet the energy demands of the main communications station throughout the winter months. However, as summer approaches, monthly wind speed drops below the speed required to fulfill the full load requirements. Wind speed eventually drops below the minimum speed for the turbine to generate any power. Consequently, a different power generating system will be needed to augment and complement this wind generating system. A solar power system would be most suitable since the decreased wind speeds occur during the summer months when solar flux is typically at its highest.

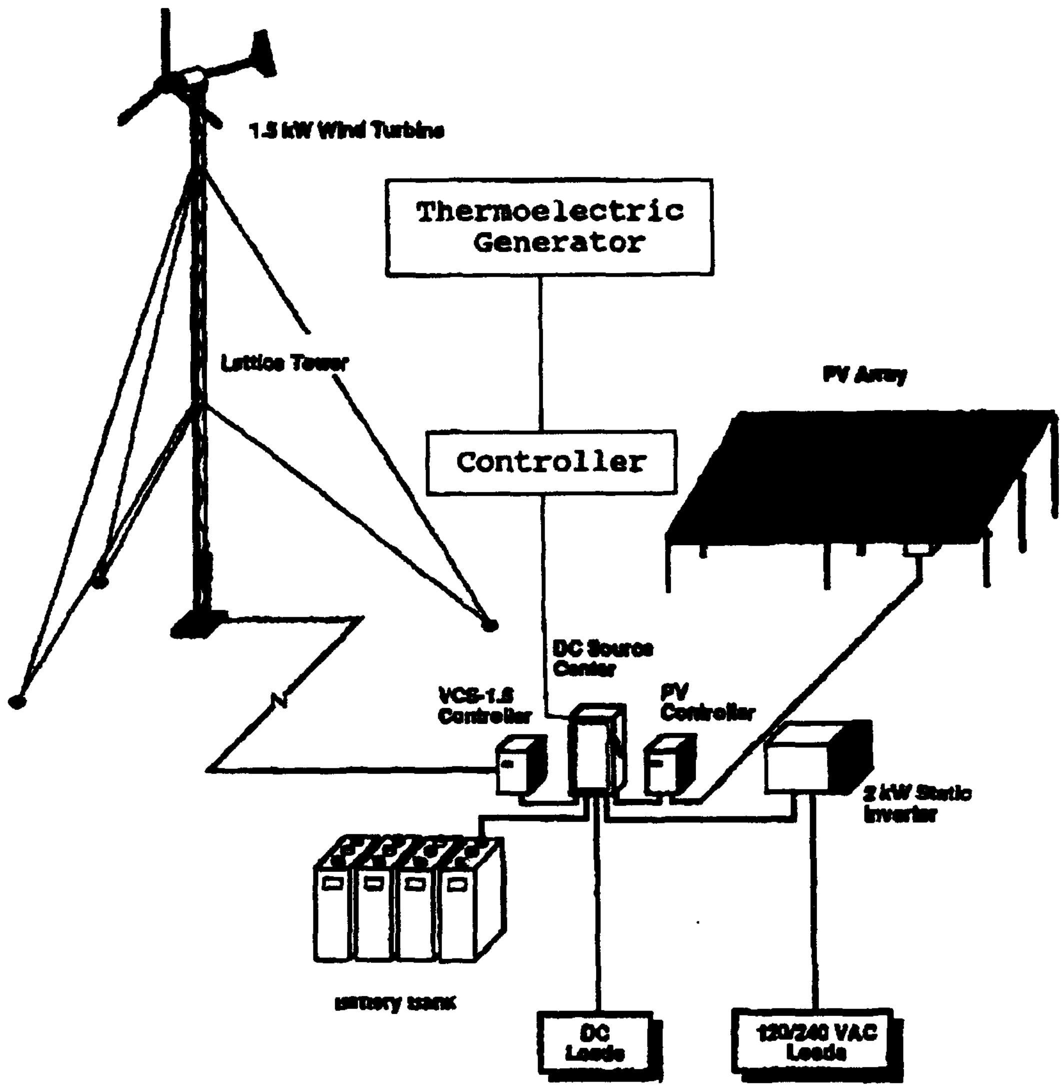

Figure 8-1. Typical Hybrid Power System [adapted from Ref.62]

2. Photovoltaic Array Component

In Chapter V, a photovoltaic array system was considered for use as the sole power source for the Coast Guard application. However, as was determined, a photovoltaic array only system, while feasible in the summer months, is not justifiable to support the entire electrical load of a main communications station in the winter months. This was mainly due to the physical size of the required array (and the significant accompanying costs). Therefore, as was discussed in Section 1, a photovoltaic array should be completely integrated with the wind-powered generator system to form the primary power system of the hybrid system.

As was documented in Chapter V, the average solar insolation striking the typical solar panel at the highest latitude site (60°) is approximately 2.5 kWh/day during the month of June. Assuming a ten percent efficiency, this translates to a 245 W/day output per panel, when the panel is tilted at the optimum 20° angle as determined by Appendix C and addressed in Chapter V.

A minimum of approximately 45 panels (0.5 m^2, 50 watts) would be required to meet the main communications system power requirement of 10.97 kWh/day. For a 55° site, a minimum of 47 panels is required, as was presented in Chapter V. Therefore, a minimum of 50 solar panels should be utilized in the array to meet the electrical power demands of the main

communications system. It should be noted that the power requirement was boosted by 30 percent to account for any losses incurred by the system [Ref.2].

Considering the surface area of a typical panel (approximately 0.5 m x 1 m), the 50 solar panels would require an area of 25 square meters, which is feasible.

3. Recommended System

This leads to the conclusion that a hybrid power system consisting of solar and wind components is an attractive and feasible solution for the Coast Guard application. The photovoltaic array component is the primary provider of power in the summer months, while the wind-power generator component produces the majority of the power needed for winter months.

The entire power system for this application would consist of:

- A single 1.5 kW wind-powered generator as described in Chapter VI.
- A photovoltaic array consisting of approximately 50 solar panels, each approximately 0.5 x 1 m for an area of 25 m^2 (4 panels, totaling 2 m^2, for the relay sites).
- A battery bank capable of supplying a minimum of 48 hours (96 for the relay sites) of power to the communication system as described in Chapter VII.
- A stand-by thermoelectric generator system for emergency use that can be automatically (low battery level) or remotely operated (system operator initiated) in case of both wind and solar system failure or interruption.

It should be noted that there is an added power benefit that is a byproduct of this design. Although power may be generated by the array in the winter months (as the wind turbine may generate power in the low wind summer months), it will not be counted upon to provide such power in support of the loads. In other words, the power generated by each component in the off-months is an added benefit of the design.

4. Problems with this Analysis

When installing a wind-powered generator system and a photovoltaic array for power production, site analysis is extremely important. In a typical situation there would be at least a limited choice of sites. This was the case for this application. Accurate wind and insolation analysis was not conducted, nor was optimum positioning of the sites determined, due to previous site selection by the Coast Guard.

Historical information on mean wind speeds and solar insolation data (Appendices C, D and E) was obtained from long term records for the region under consideration. However, accurate wind and insolation data for specific site locations were not available. The historical data was taken as representative of the actual site data, if for no other reason than it was the only data available in the area of interest surrounding the actual remote sites.

IX. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

There is a wide variety of available power supply options for small stand-alone communications applications and an even greater and almost bewildering choice of "potentially" useful options that are for one reason or another not adequately developed. For this specific application, the selection of a wind/photovoltaic hybrid system was correct. However, all possible alternatives must be evaluated with respect to other remote applications.

B. CONCLUSIONS

This research represents the first iteration in the design of a hybrid power system for use in the Coast Guard application in Alaska. Several important conclusions can be drawn from this study.

First, there are several alternative power supplies that can be utilized to provide power for communications sites in remote locations.

Second, a hybrid design can be utilized to support the electrical loads of the Coast Cuard specific application.

Third, commercially available off-the-shelf components can be utilized in the hybrid system discussed in Chapter VIII.

Lastly, the experience obtained in designing a hybrid system led to a greater appreciation for the choices that must be made when faced with a number of options.

As stated at the outset, the intention of this research was not to design an actual hybrid power supply for the Coast Guard application. The objective was to ascertain whether the alternatives or a combination of alternatives were viable options to replace or be used in conjunction with the existing thermoelectric generator. From the investigation it can be concluded that alternatives can be utilized to supply the electrical loads. However, the problem was not solved through the selection of any one alternative, but rather by a combination.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

The author makes the following recommendations for future research:

- Verify the system design by monitoring and evaluating the performance and reliability of the installed equipment with respect to the achievement of meeting the design requirements.
- Investigate the potential of fuel cell utilization in remote power system design when fuel cell technology reaches the commercial stage.
- Monitor selected sites to obtain detailed wind and insolation data in order to optimize the power system design.
- Explore the geothermal possibility for remote site power supplies.

APPENDIX A. COASTAL VOICE DISTRESS NETWORK SITES

Site Name	Latitude	Longitude	Elevation
Duke Island	54-52-40N	131-22-35W	1700 feet
Sukkwan Island	55-05-08N	132-46-22W	2200 feet
Gravina Island	55-21-42N	131-22-35W	2506 feet
Lincoln Rock	56-03-28N	132-41-20W	50 feet
Zarembo Island	56-20-45N	132-51-35W	2444 feet
Sitkinak Dome	56-33-34N	154-10-56W	1640 feet
Cape Fanshaw	57-12-20N	133-29-15W	2256 feet
Kruzof Island	57-18-37N	135-42-02W	1300 feet
Moore Mountain	57-37-21N	135-23-20W	2100 feet
Cape Bingham	58-04-33N	136-27-57W	1740 feet
Cape Gull	58-12-10N	154-12-10W	1440 feet
Robert Barren Peak	58-13-40N	134-50-25W	3475 feet
Marmot Island	58-14-14N	151-49-20W	1229 feet
Tuklung Mountain	58-51-30N	159-27-50W	1630 feet
Bede Mountain	59-18-40N	151-56-45W	2000 feet
Rugged Island	59-51-40N	149-23-15W	1436 feet
Chenega Island	60-18-05N	148-03-16W	1000 feet
Naked Island	60-38-49N	147-20-36W	1215 feet
Point Pigot	60-49-07N	148-22-38W	1300 feet

[adapted from Ref.50:p.13]

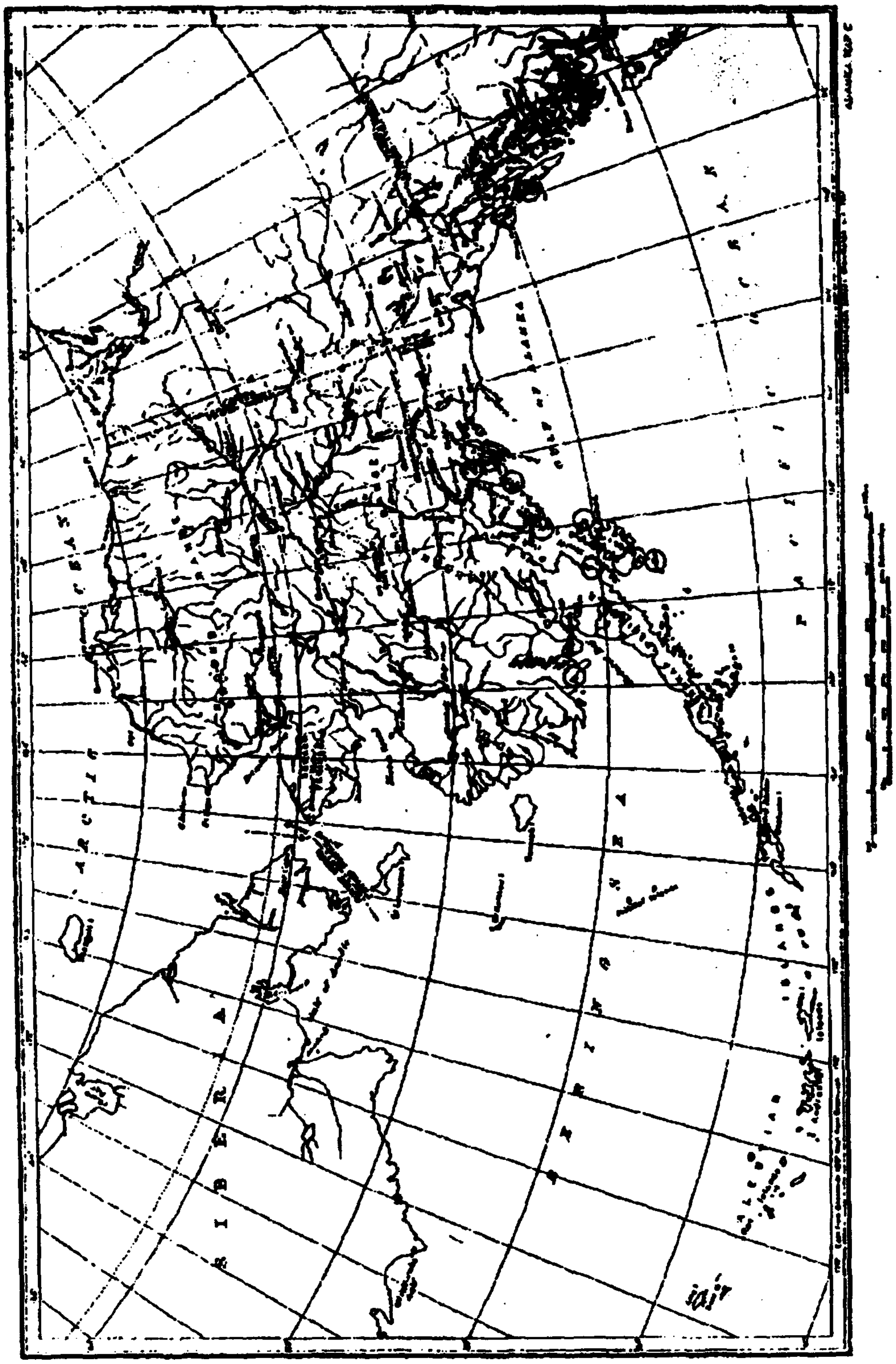

Figure A-1. Communications Site Locations [Ref.44:p.14]

APPENDIX B. AVERAGE INSOLATION ESTIMATES (kWh/m^2)

Location	°N Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Calcutta	22	6.2	7.2	8.2	9.1	9.1	9.5	9.5	9.3	7.5	7.3	6.5	5.8
Tuscon	32.5	3.7	4.6	5.3	7.6	8.5	8.1	7.3	6.9	6.6	5.1	4.1	3.5
Tokyo	36	2.2	2.7	3.2	3.6	4.0	3.5	3.9	3.9	2.9	2.4	2.2	1.9
New York	42	1.4	2.2	3.0	4.2	4.9	5.2	5.1	4.3	3.7	2.8	1.7	1.3
Brussels	51	0.7	1.3	2.4	4.0	4.7	5.1	4.7	4.1	2.9	1.8	0.9	0.6
Juneau	58.5	0.4	0.9	1.9	3.3	4.1	4.5	4.0	3.1	2.0	1.0	0.5	0.2
Nome	64.5	0.1	0.7	1.9	3.7	4.5	5.5	4.5	3.1	2.1	0.9	0.2	0.0

APPENDIX C. AVERAGE DAILY INSOLATION ESTIMATES

The tables on the following two pages are from the *Handbook of Solar Energy Data for South-Facing Surfaces in the United States* [Ref.63]. They show the average daily insolation estimates (kWh/m^2) for each month and the estimated annual amounts for two representative sites in Alaska.

AVERAGE DAILY TOTAL TERRESTRIAL INSOLATION ESTIMATES (KWH/SQ. M)

SITE: ADAK AK
LATITUDE: 51 DEGREES 53 MINUTES

AVERAGE DAILY AMOUNTS BY MONTH

ARRAY TILT	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL AMOUNT	AVERAGE DAY
0.0	0.73	1.36	2.25	3.25	3.72	3.72	3.53	2.99	2.39	1.66	0.97	0.59	827.7	2.3
10.0	0.90	1.56	2.47	3.40	3.79	3.76	3.60	3.12	2.63	1.98	1.28	0.79	892.2	2.4
15.0	0.98	1.66	2.55	3.46	3.80	3.76	3.60	3.17	2.72	2.12	1.43	0.89	917.8	2.5
20.0	1.05	1.74	2.63	3.49	3.80	3.73	3.60	3.19	2.80	2.25	1.57	0.98	938.9	2.6
25.0	1.12	1.81	2.69	3.51	3.77	3.69	3.57	3.20	2.87	2.37	1.70	1.07	955.4	2.6
30.0	1.18	1.87	2.73	3.51	3.73	3.64	3.53	3.20	2.92	2.47	1.82	1.15	966.9	2.6
35.0	1.24	1.92	2.76	3.49	3.67	3.57	3.48	3.18	2.96	2.56	1.92	1.22	973.4	2.7
40.0	1.29	1.97	2.78	3.45	3.60	3.48	3.40	3.14	2.98	2.63	2.02	1.28	974.8	2.7
45.0	1.33	2.00	2.78	3.40	3.50	3.38	3.31	3.09	2.98	2.69	2.10	1.34	971.1	2.7
50.0	1.36	2.02	2.77	3.33	3.39	3.27	3.21	3.03	2.97	2.73	2.17	1.38	962.3	2.6
60.0	1.40	2.02	2.70	3.14	3.14	3.01	2.97	2.86	2.90	2.76	2.26	1.45	931.4	2.6
70.0	1.41	1.98	2.57	2.90	2.84	2.70	2.69	2.63	2.76	2.73	2.29	1.48	881.8	2.4
80.0	1.38	1.89	2.39	2.60	2.49	2.36	2.36	2.37	2.57	2.63	2.27	1.48	814.5	2.2
90.0	1.32	1.77	2.16	2.26	2.12	2.01	2.01	2.06	2.32	2.46	2.18	1.43	732.8	2.0

Insolation Estimates [Ref.63:p.C-2]

AVERAGE DAILY TOTAL TERRESTRIAL INSOLATION ESTIMATES (KWH/SQ. M)

SITE: BETHEL AK
LATITUDE: 60 DEGREES 47 MINUTES

ARRAY TILT	AVERAGE DAILY AMOUNTS BY MONTH J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL AMOUNT	AVERAGE DAY
0.0	0.31	1.00	2.33	3.79	4.58	4.79	4.07	2.90	2.21	1.17	0.43	0.15	845.0	2.3
10.0	0.45	1.27	2.72	4.11	4.76	4.91	4.22	3.10	2.56	1.54	0.72	0.28	933.6	2.6
15.0	0.52	1.40	2.89	4.23	4.82	4.94	4.26	3.18	2.71	1.72	0.86	0.34	970.9	2.7
20.0	0.59	1.52	3.05	4.34	4.85	4.94	4.28	3.24	2.85	1.88	0.99	0.39	1003.0	2.7
25.0	0.65	1.62	3.19	4.42	4.86	4.92	4.28	3.28	2.98	2.04	1.12	0.45	1029.6	2.8
30.0	0.71	1.72	3.31	4.47	4.85	4.88	4.26	3.31	3.08	2.18	1.24	0.50	1051.0	2.9
35.0	0.77	1.81	3.41	4.50	4.81	4.82	4.23	3.32	3.17	2.30	1.35	0.55	1067.0	2.9
40.0	0.82	1.89	3.49	4.51	4.75	4.74	4.17	3.31	3.24	2.42	1.45	0.59	1077.0	3.0
45.0	0.86	1.96	3.54	4.49	4.67	4.64	4.09	3.28	3.29	2.51	1.54	0.64	1080.9	3.0
50.0	0.90	2.01	3.58	4.44	4.56	4.51	4.00	3.24	3.32	2.59	1.62	0.67	1078.6	3.0
60.0	0.96	2.08	3.59	4.27	4.27	4.18	3.74	3.10	3.32	2.70	1.75	0.73	1055.8	2.9
70.0	0.99	2.10	3.51	4.02	3.92	3.81	3.43	2.91	3.24	2.74	1.83	0.77	1012.4	2.8
80.0	1.00	2.06	3.35	3.69	3.50	3.37	3.07	2.67	3.08	2.70	1.86	0.79	946.8	2.6
90.0	0.98	1.98	3.10	3.27	3.02	2.88	2.65	2.37	2.85	2.60	1.83	0.78	860.8	2.4

Insolation Estimates [Ref.63:p.C-4]

APPENDIX D. AVERAGE WIND SPEEDS (MPH)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Anchorage	5.8	6.6	6.7	7.1	8.3	8.2	7.1	6.5	6.1	6.4	6.1	6.0
Annette	12.1	12.3	11.1	11.2	9.4	9.0	8.1	8.3	9.4	12.0	12.4	12.8
Barrow	11.3	10.9	11.1	11.4	11.6	11.3	11.6	12.3	13.0	13.3	12.4	11.1
Barter	14.8	14.2	13.7	11.9	12.5	11.5	10.6	11.7	13.1	14.6	15.0	13.9
Bethel	14.1	15.1	13.7	13.4	11.7	11.7	11.2	11.2	11.6	12.6	13.5	14.0
Bettles	5.8	6.8	7.4	7.6	7.6	7.1	6.5	6.1	6.7	6.7	6.1	5.9
Big Delt	10.8	9.9	8.2	7.6	7.9	6.5	6.0	6.6	7.3	8.5	9.5	9.5
Cold Bay	17.8	17.8	17.4	18.2	16.2	15.9	15.7	16.4	16.2	16.8	17.6	17.0
Fairbanks	2.9	3.9	5.1	6.5	7.7	7.0	6.5	6.1	6.1	5.4	3.9	3.2
Gulkana	5.1	5.6	6.5	8.6	8.8	8.8	8.2	8.0	7.6	6.3	4.8	3.6
Homer	7.8	7.7	7.4	7.3	7.7	7.0	6.8	5.7	6.2	6.8	7.5	7.1
Juneau	8.4	8.8	8.8	8.8	8.5	7.8	7.6	7.5	8.0	9.7	8.7	9.2
Kodiak	12.4	12.1	11.8	10.9	10.1	8.3	7.0	7.6	9.0	10.7	12.0	12.2
Kotzebue	14.8	12.7	12.5	12.9	10.9	12.4	13.0	13.3	13.2	13.6	14.6	12.7
Mc Grath	2.8	4.1	5.1	6.3	6.5	6.2	5.9	5.6	5.6	5.1	3.5	3.1
Nome	11.8	11.1	10.5	10.8	10.3	10.1	10.1	10.7	11.3	11.2	12.2	10.3

[Ref.42:pp.286-287]

APPENDIX E. ALASKA WIND SPEED MAPS

The figures on the following four pages are from the *Northwest, Northcentral and Alaska Wind Atlas* [Ref.53] and the *Wind Energy Resource Atlas of the United States* [Ref.64]. They show a summary of the wind energy resource in the Alaskan region. The numbers on the maps indicate the wind class of the area (ridge crest estimates). The ridge crest estimates correspond to the table shown in Figure E-1. A latitude-longitude grid is superimposed on the last three maps to facilitate the location of specific areas on the maps. Each grid cell is 1/2° in latitude by 1° in longitude.

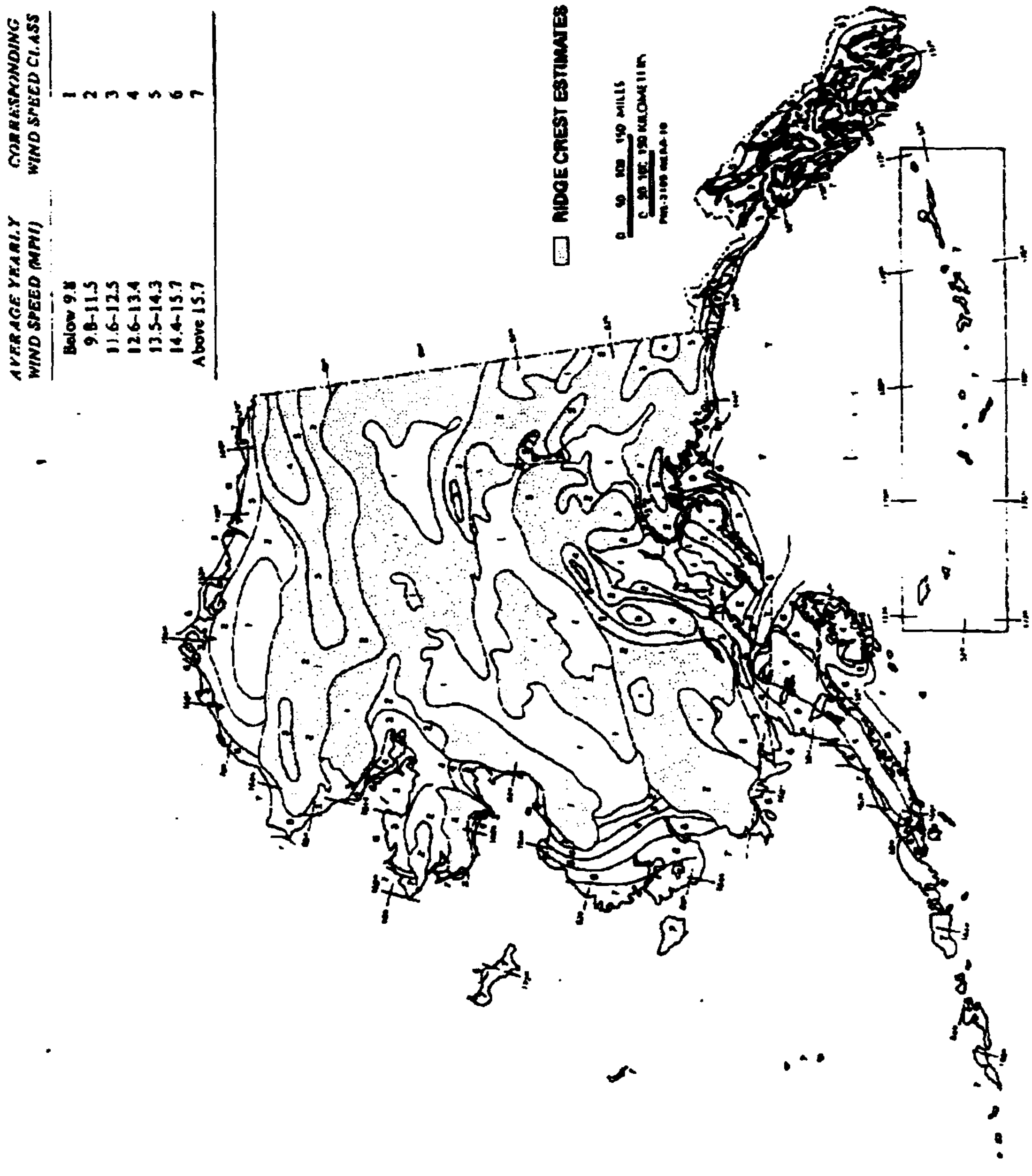

Figure E-1. Yearly Average Wind Speeds in Alaska [Ref.Atlas:p.118]

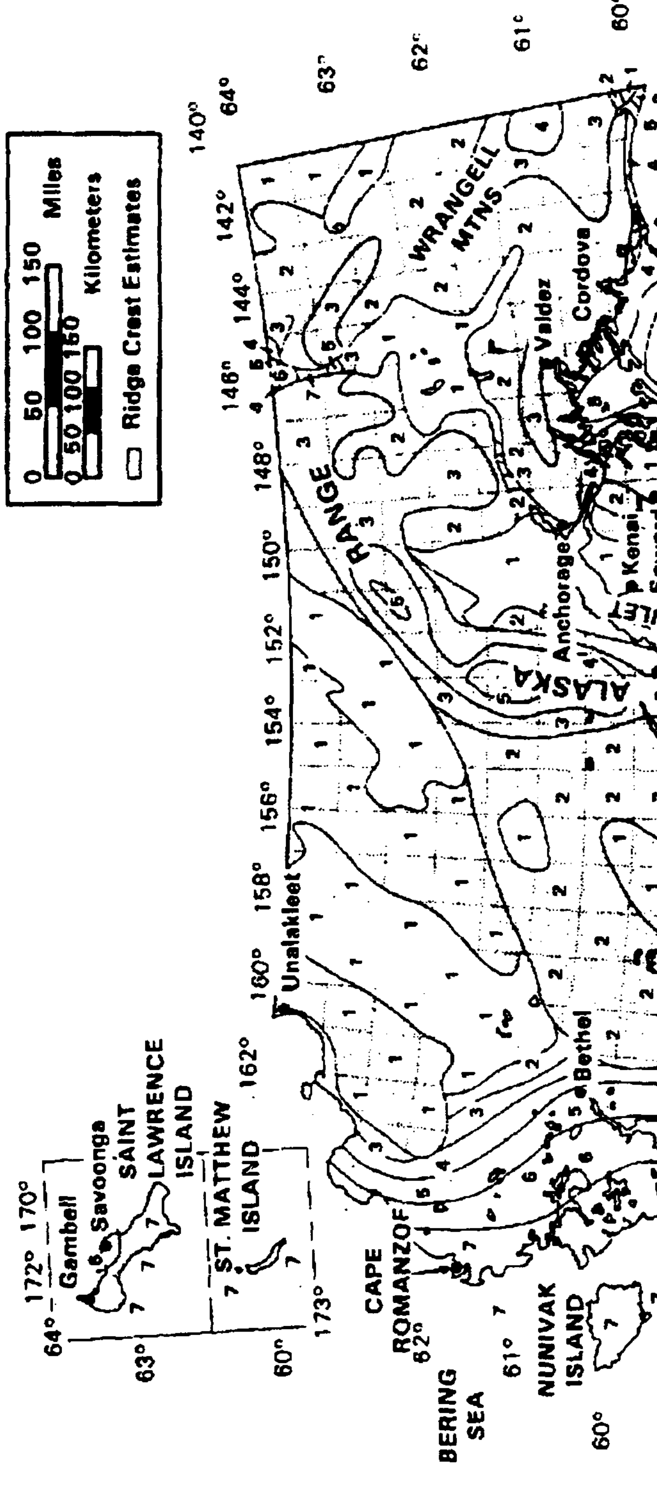

Figure E-2. South-Central Alaska Annual Average Wind Power [Ref.64:p.120]

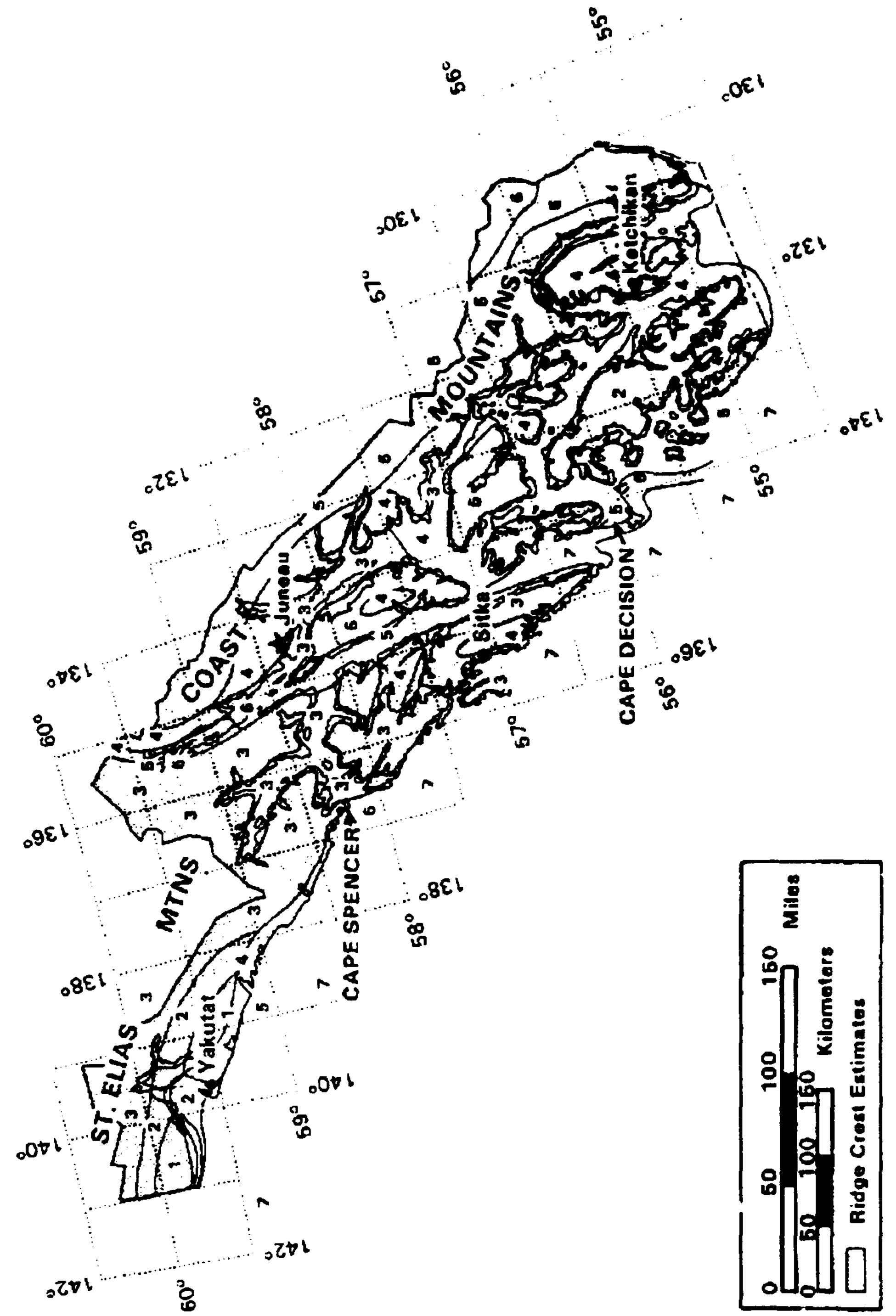

Figure E-3. Southeastern Alaska Average Annual Wind Power [Ref.64:p.121]

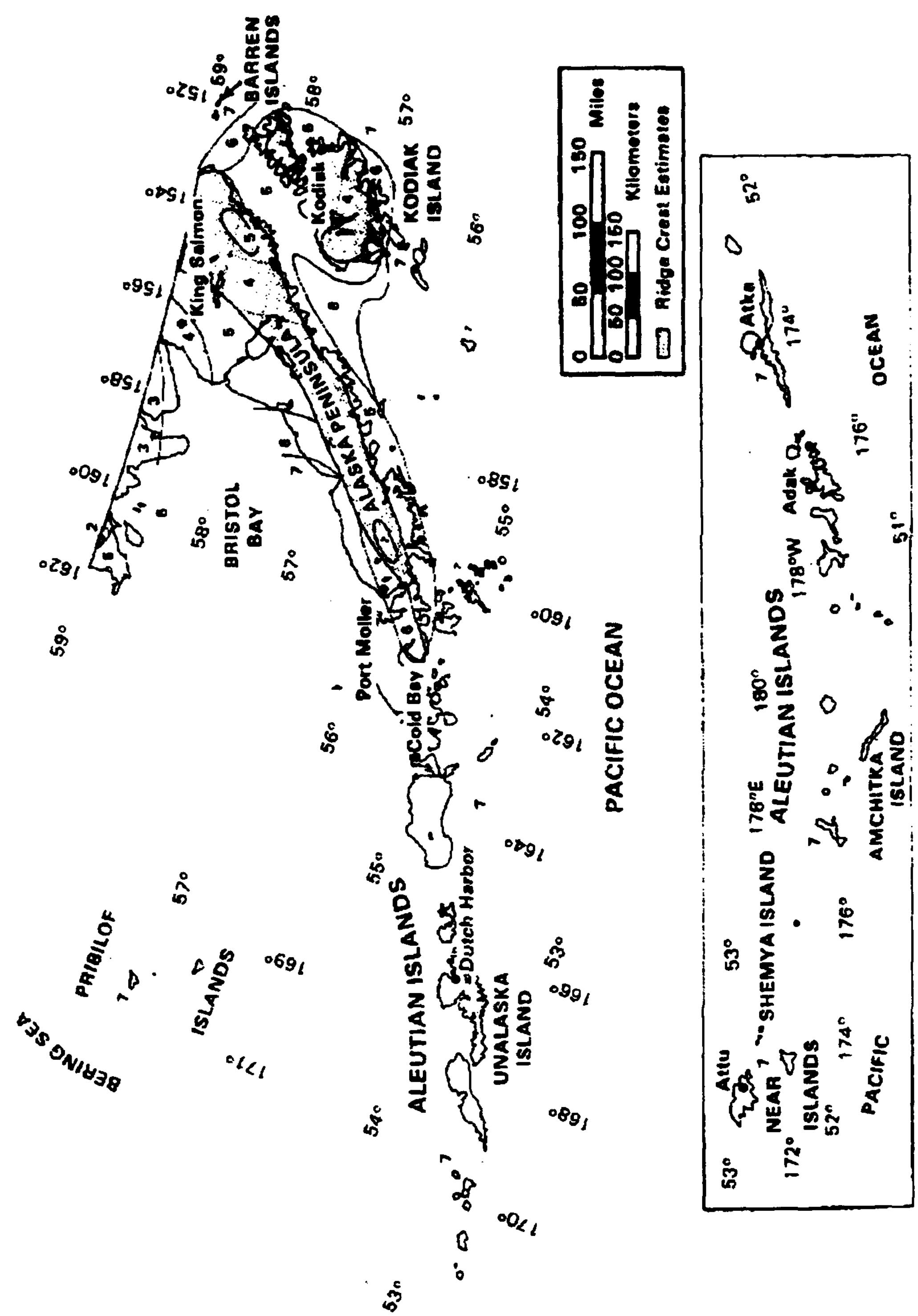

Figure E-4. Southwestern Alaska Average Annual Wind Power [Ref.64:p.122]

LIST OF REFERENCES

1. Maintenance and Logistics Command Pacific specification, *Hybrid Power System for Remote Communication Sites*, October, 1992.

2. Personal Conversation between Dr. Sherif Michael, Naval Postgraduate School, and the author, April 1993.

3. International Telegraph and Telephone Consultative Committee (CCITT), *Primary Sources of Energy for the Power Supply of Remote Telecommunications Systems*, by International Telecommunications Union (ITU), Special Autonomous Working Group No. 4 (GAS 4), Geneva, 1985.

4. Fraenkel, P.L., "An Overview of Power Supply Options," *Wind Engineering*, vol. 14, no. 3, 1990.

5. *Direct Energy Conversion*, edited by G.W. Sutton, McGraw-Hill Book Co., New York, 1966.

6. Angelo, J.A., Jr., and Buden, D. *Space Nuclear Power*, Orbit Book Company, Inc. Malabar, Florida, 1985.

7. Meinel, A.B. and Meinel, M.D., *Applied Solar Energy*, Addison-Wesley Publishing Co., 1976.

8. Aschner, F.S., *Planning Fundamentals of Thermal Power Plants*, Keter Publishing House, Jerusalem, 1978.

9. *Space Nuclear Power Systems 1989*, edited by M.S. El-Genk and M.D. Hoover, Orbit Book Company, Inc. Malabar, Florida, 1992.

10. Armstrong, L.V., and Hartman, J.B., *The Diesel Engine*, The Macmillan Company, New York, 1959.

11. Salisbury, J.K., *Steam Turbines and their Cycles*, John Wiley and Sons, Inc., New York, 1950.

12. Reader, G.T., and Hooper, C., *Stirling Engines*, University Press, Cambridge, 1983.

13. Lapendes, D.N., *Encyclopedia of Energy*, McGraw-Hill Book Co., New York, 1976.

14. Kreith, F. and Kreider, J.F., *Principles of Solar Engineering*, Hemisphere Publishing Corp., Washington, 1978.

15. Anderson, B. and Riordan, M., *The Solar Home Book: Heating, Cooling and Designing with the Sun*, Cheshire Books, 1976.

16. Daniels, F., *Direct Use of the Sun's Energy*, McGraw-Hill Book Co., New York, 1974.

17. Jet Propulsion Laboratory Publication SP 43-38, *Solar Cell Array Design Handbook*, v. 1, October 1976.

18. Wolf, M., "Photovoltaic Solar Energy Conversion Systems," *Solar Energy Handbook*, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1981.

19. Green, M.A., *Solar Cells: Operating Principles, Technology, and System Applications*, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1982.

20. Wolf, M., "Historical Development of Solar Cells," *Proceedings of the 25th Power Sources Symposium*, May 1972.

21. Rauschenbach, H.S., *Solar Cell Array Design Handbook*, Van Nostrand Reinhold Co., New York, 1980.

22. Maxwell AFB Report No. 1855-77, *Some Guidelines for the Planning and Programming of Facilities Applications of Solar Energy*, by M.W. Nay, Jr., March 1977.

23. Johnson, F.S., "The Solar Constant," *Meteorology*, v. 11, December 1954.

24. Solar Energy Research Institute, SERI/SP-755-789, *Insolation Data Manual*, by C.L. Knapp, October, 1980.

25. Solar Energy Research Institute, SERI/SP-642-1037, *Solar Radiation Energy Resource Atlas of the United States*, October 1981.

26. Hu, C., and White, R.W., *Solar Cells: From Basics to Advanced Systems*, McGraw-Hill Book Co., New York, 1983.

27. National Science Foundation, Report No. NSF/RA/N-73-111A, *Systems Analysis of Solar Energy Programs*, by Solar Study Team, MITRE Corporation, December 1973.

28. U.S. Department of Health, Education and Welfare, Publication No. HRA/76-620, *Energy Strategies for Health Care Institutions*, April 1976.

29. Jet Propulsion Laboratory Publication 82-69, *Solar Cell Radiation Handbook*, 3rd ed., 1 November 1982.

30. Merrigan, J.A., *Sunlight to Electricity*, MIT Press, 1976.

31. Solar Energy Research Institute, *Basic Photovoltaic Principles and Methods*, Van Nostrand Reinhold Co., New York, 1984.

32. Wurfel, P. and Ruppel, W., "Thermodynamic Limitations for Direct Solar Energy Conversion," *Third Photovoltaic Solar Energy Conference*, D. Reidel Publishing Co., October 1980.

33. Mabie, K.T., *Solar Simulation Laboratory Description and Manual*, Master's Thesis, Naval Postgraduate School, Monterey, California, June, 1985.

34. Southwest Technology Development Institute, *Photovoltaic Power Systems and the National Electrical Code*, New Mexico University, Las Cruces, November 1992.

35. Sandia Laboratories, *Maintenance and Operation of Stand-Alone Photovoltaic Systems*, Albuquerque, New Mexico, December 1991.

36. Palz, W., *Solar Electricity*, Chapel River Press, Andover, England, 1980.

37. Boes, E.C., "Photovoltaic Concentrator Progress," *The Conference Record of the Sixteenth IEEE Photovoltaic Specialists Conference - 1982*, IEEE Publishing Service, New York, 1983.

38. Cummings, R.D., "Solar Energy for Health Care Institutions," *The Journal*, May 1976.

39. Photovoltaic Module specification, *LA361J51 High Efficiency Multicrystal Photovoltaic Module*, Kyocera America, Inc., San Diego, California, September 1992.

40. Eggleston, D.M., and Stoddard, F.S., *Wind Turbine Engineering Design*, Van Nostrand Reinhold Company, New York, 1987.

41. Cheremisinoff, N.P., *Fundamentals of Wind Energy*, Ann Arbor Science Publishers, Inc., Ann Arbor, 1978.

42. Mirriam, M.F., "Wind Energy for Human Needs," *Technology Review*, v. 79, no. 3, January 1977.

43. Noyes Data Corporation, *Wind Power: Recent Developments*, edited by D.J. De Renzo, New Jersey, 1979.

44. Inglis, D.R., *Windpower and Other Energy Options*, University of Michigan Press, Ann Arbor, 1978.

45. National Aeronautics and Space Administration NASA SP-455, *Capturing Energy From The Wind*, by J.L. Schefter, Washington, D.C., 1982.

46. Golding, E.W., and Harris, R.I., *The Generation of Electricity by Wind Power*, Halstead Press, New York, 1976.

47. Marier, D., *Wind Power for the Homeowner*, Rodale Press, Emmaus, Pennsylvania, 1981.

48. Sandia Laboratories SAND 74-0348, *Wind Power Climatology of the United States*, by J.W. Reed, Albuquerque, New Mexico, 1975.

49. Solar Energy Research Institute, SERI/SP-271-2684, *Wind Energy Technical Information Guide*, March 1985.

50. U.S. Fish and Wildlife Service, *An Evaluation of Raptor Related Impacts at 19 Proposed Wind Turbine Sites in Coastal Alaska*, by P.F. Schempf, Juneau, Alaska, November 1992.

51. BWC 1500 Series specification, *The BWC 1500 Wind Energy Systems*, Bergey Windpower Company, Inc., Norman, Oklahoma, September, 1990.

52. Wentink, T., *Jr., Study of Alaskan Wind Power and Its Possible Applications*, University of Alaska, Fairbanks, 1976.

53. Solar Energy Research Institute, *Northwest, Northcentral and Alaska Wind Atlas*, 1987.

54. Bergey, K.H., *Feasibility of Wind Power Generation for Central Oklahoma*, University of Oklahoma, Norman, Oklahoma, 1971.

55. Lipman, N.H., "Autonomous Wind-Diesel System for Remote Application," *Wind Engineering*, vol. 12, no. 3, 1988.

56. *Space Nuclear Power Systems 1985*, edited by M.S. El-Genk and M.D. Hoover, Orbit Book Company, Inc. Malabar, Florida, 1986.

57. S. Michael, Notes for EO3740 (Space Power and Radiation Effects), Naval Postgraduate School, 1993 (unpublished).

58. Noll, E.M., *Wind/Solar Energy for Radiocommunications and Low-Power Electronic/Electric Applications*, Howard W. Sams & Co., Inc., Kansas City, 1975.

59. BWC 1500 Series technical manual, *Windpower Generator: Owner's Manual and Parts List*, Bergey Windpower Company, Inc., Norman, Oklahoma.

60. Barak, M., *Electrochemical Power Sources: Primary & Secondary Batteries*, The Institution of Electrical Engineers, New York, 1980.

61. Webster's Ninth New Collegiate Dictionary, Mirriam-Webster, Inc., 1985.

62. Typical Remote Hybrid Power System drawing, supplied by Bergey Windpower Company, Inc., Norman Oklahoma.

63. Jet Propulsion Laboratory, JPL Publication 79-103, *Handbook of Solar Energy Data for South-Facing Surfaces in the United States*, Volume 1, by J.H. Smith, January, 1980.

64. Solar Energy Research Institute, DOE/CH 10093-4, *Wind Energy Resource Atlas of the United States*, by D.L. Elliot and others, October 1986.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria VA 22304-6145	2
2.	Library, Code 052 Naval Postgraduate School Monterey CA 93943-5002	2
3.	Chairman, Code EC Department of Electrical and Computer Engineering Naval Postgraduate School Monterey, CA 93943-5121	1
4.	Dr. Sherif Michael, Code EC/Mi Department of Electrical and Computer Engineering Naval Postgraduate School Monterey, CA 93943-5121	2
5.	Dr. Robert W. Ashton, Code EC/Ah Department of Electrical and Computer Engineering Naval Postgraduate School Monterey, CA 93943-5121	1
6.	Commander Maintenance and Logistics Command Pacific (tts-1) ATTN: CWO4 Daniel C. Slagle Coast Guard Island Alameda, CA 94501-5100	2
7.	LCDR Christopher R. Pietras 11095 Addison Street Spring Hill, FL 34609	2